FLOW PATTERNS AND EVAPORATION IN COCURRENT SPRAY-DRYERS

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by

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CONTENTS

SUMMARY

A cocurrent two-stage spray dryer was designed and built, and its performance investigated by means of residence time distribution (R.T.D.) analysis for both the continuous phase and the dispersed phase. Analytical methods using transfer functions were developed and found to be very useful in interpreting the data obtained.

In the present equipment the flow pattern of the drying gas was found by these methods to consist of a well-mixed zone and a plug-flow zone in series. The presence of a pneumatic nozzle had a very large effect on the flow pattern in the chamber, in spite of the small atomising air rate used. The Craya-Curtet number Ct (the square root of the drying air momentum / atomising air momentum ratio) correlated this effect well, the atomising air stream becoming dominant as Ct becomes somewhat less than one, a result already found in other contexts. An interesting phenomenon is the existence of a minimum dispersion point at Ct $\simeq$ 0.25. All these results were confirmed by hot-wire anemometry and flow visualisation with smoke.

The droplet-phase R.T.D. yielded some useful information on the degree of entrainment of droplets into the air stream. This entrainment could be correlated by a newly derived parameter involving the Lagrangian scale of turbulence, the intensity of fluid turbulence and the inertia of the droplet to velocity fluctuations in the fluid.

Finally a method of performance prediction for cocurrent spray dryers was developed, using a stepwise computation and paying special attention to the jet zone and the effect of solute or suspended solids in the feed. The predictions of the method agree well with existing data, but also pointed out the need for more experiments on the drying

of single droplets of industrially important materials. Methods for taking R.T.D. effects into account were discussed and illustrated.

INTRODUCTION

Spray drying is the process whereby a solid-liquid mixture is atomised and brought into contact with a hot gas to yield a dried powder. The atomisation increases greatly the surface/volume ratio of the mixture, enabling the drying to take place in a very short time, typically of order 2 - 20 s. The process is thus particularly suitable for heat-sensitive products or when the solubility of the product must be large. In New Zealand spray drying is of particular importance in view of the large scale production of milk powder.

Although the process of spray drying has existed for more than a hundred years and considerable research has been done on it,[M5,M7,M8, L6,B17] the design and performance prediction of spray dryers in practice are still mostly a matter of empiricism. The process is simple in principle, but a large number of parameters can affect the results. Furthermore, the design pattern varies greatly from dryer to dryer and a different approach may be preferable in each case.

Some of the basic investigations of heat, mass and momentum transfer and of turbulence effects have previously been carried out in this department [B17]. It seemed logical that the next step should be to move closer to an industrial type situation, and to study the performance of a realistic spray dryer. Therefore this work consisted of three parts:

1) The design and construction of a spray dryer (chapter 1).

2) The investigation of both continuous and dispersed-phase flow patterns, using residence-time distributions with some new developments in transfer-function analysis (chapters 2, 3 and 4). From the data obtained, insights can be gained on how to improve the design of this and similar models or to optimise their operation.

3) The development of a method of evaporation prediction in this type of spray dryer (chapters 5 and 6).

CHAPTER 1.

THE SPRAY DRYER

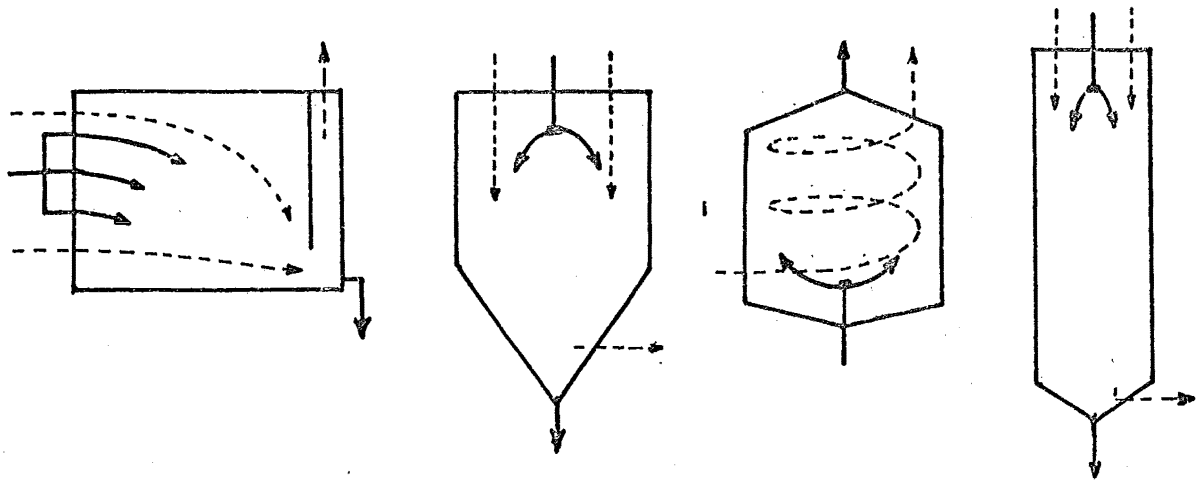
Chapter contents:

I. DESIGN CONSIDERATIONS

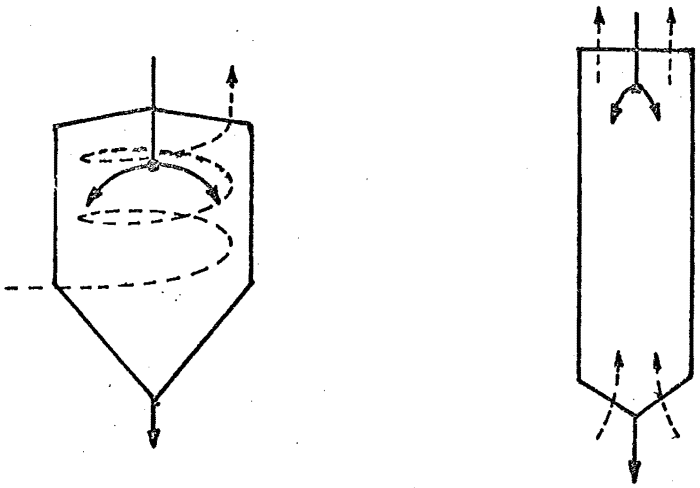
Industrial spray dryers come in a great diversity of sizes, shapes, flow and atomising arrangements. The general geometry varies from squat-looking chambers with a 1/1 length-to-diameter (or height-to-width) ratio to tall-form dryers with a 4/1 ratio. Flow regimes may be cocurrent, countercurrent, crossflow or mixed, dominantly axial or tangential, horizontal or vertical, upward or downward (figure 1). Atomising can be done with rotary atomisers (discs, cups or vaned wheels), pressure nozzles, pneumatic nozzles (with external or internal mixing) or a combination of these (figure 2). Atomisers can be positioned at the top, at the bottom or on the side walls of the drying chamber.

Experimental workers,on the other hand, tend to work with chambers having a high length-to-diameter ratio, typically 10/1 or more, using cocurrent flow with a nozzle atomiser on top. This set-up allows easy control of the flow pattern and precise measurements of the temperature, humidity, evaporation and other profiles. One such dryer has been built and studied in this department[B17].

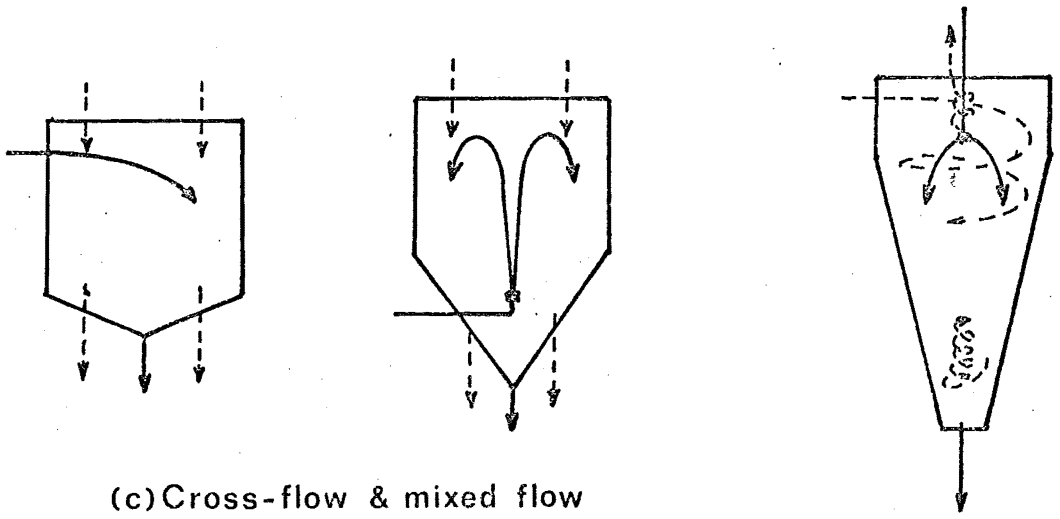
Therefore, for the present work, a compromise has been made in building a drying chamber which would not deviate too much from the geometry of industrial installations, and yet would enable the flow pattern to be easily controlled should such a need arise. The result is a tall-form (5/1 length-to-diameter ratio) dryer with downward cocurrent flow, a central nozzle atomiser and axially directed air inlets. From an economic point of view, cocurrent flow does not maximise thermal or volumetric efficiency, but it gives good control of the product quality since hot inlet air does not come into contact with dry product. Hence this kind of flow is particularly suitable



(a) Cocurrent flow



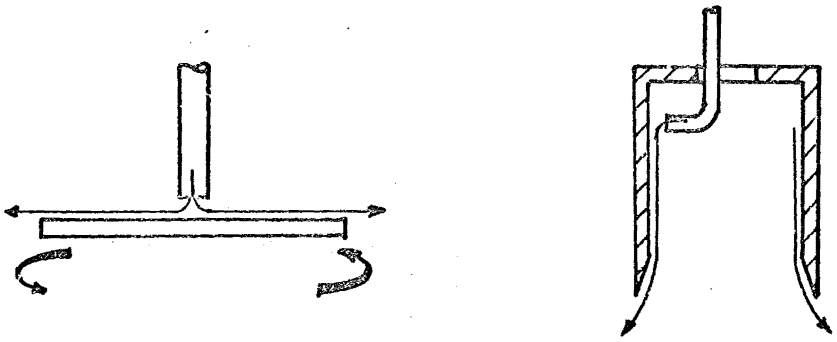
(b) Countercurrent flow



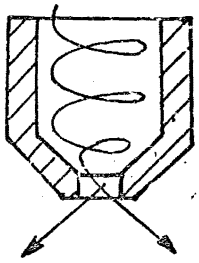
(c) Cross-flow & mixed flow

- - - - - - - - → Gas ——————→ Feed or product

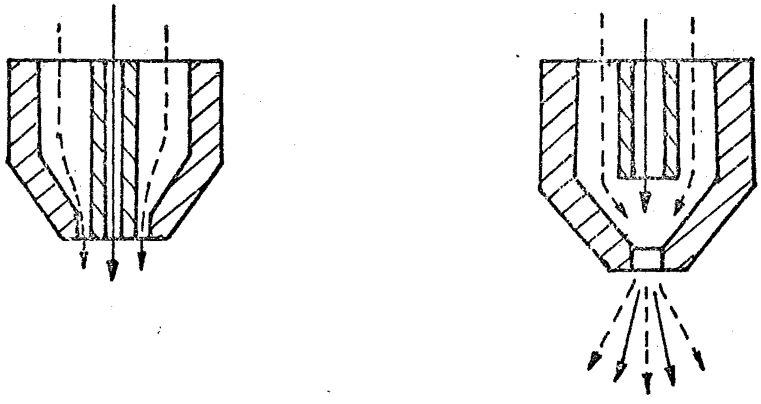
FIGURE 1.1: GEOMETRY OF INDUSTRIAL SPRAY DRYERS (H5, M5, M8)



(a) Rotary



(b) Pressure



External mixing Internal mixing

(c) Pneumatic or twin-fluid

——————→ Feed - - - - - - - - → Atomising gas

FIGURE 1.2: BASIC ATOMISER TYPES

for heat-sensitive products such as foodstuffs.

To improve the performance of the unit, a second stage pneumatic dryer has been added. Such a configuration has been suggested before (D9) and used in the dairy industry (B2). Apart from being volumetrically more efficient than a single big drying chamber, it may also give better product quality, as the almost dry powder can be dried more gently in the cooler 2nd stage.

General quantitative specifications for the design of the equipment are as follows:

- First-stage air velocity: 0.1 - 3.0 m/s,
  inlet air temperature: up to 250°C.
- Second-stage air velocity: 5. - 25. m/s,
  inlet air temperature: up to 150°C.
- Estimated maximum droplet size: 150 μm.

II. DESCRIPTION OF INSTALLATION

II.1 General layout

The flow diagram of the installation is shown in figure 3. The main part of the air from the blower goes through the heaters, but some of it bypasses the heaters and cools the bus bars of the electric air heating elements. The two streams merge again and go to the first stage.

After the first stage, the air is separated from the products by a cyclone, goes to a cooler-scrubber and discharges to the atmosphere. The product collected by the cyclone is transferred pneumatically by a rotary valve to the 2nd stage.

The 2nd stage, a pneumatic dryer, is fed with hot air from the heaters mentioned earlier and cold air directly from the blower, in a

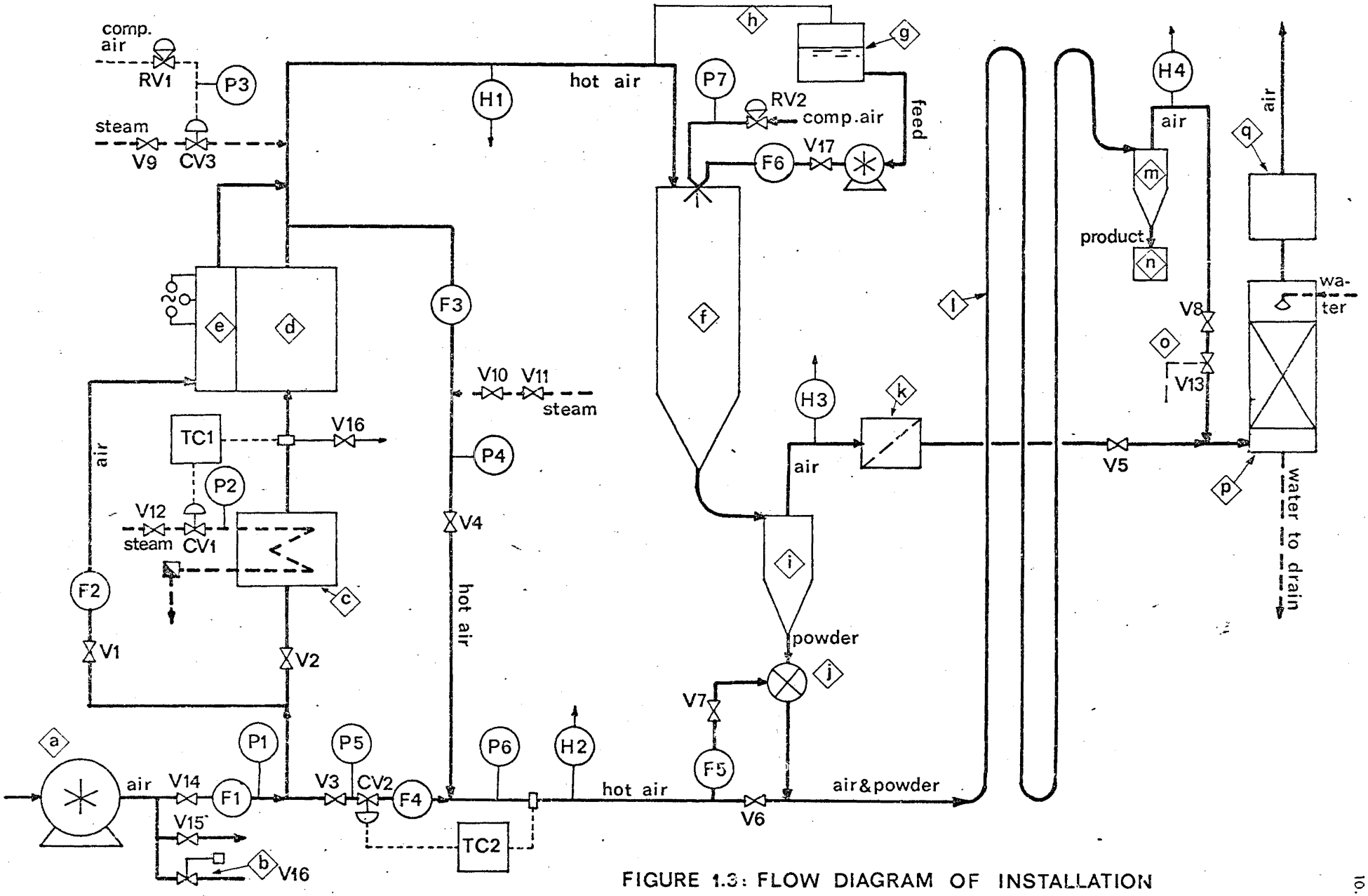


FIGURE 1.3: FLOW DIAGRAM OF INSTALLATION

Legend for Figures 1.3 and 1.4

(a) Blower.

(b) Relief valve, set at 24 k Pa.

(c) Steam heater.

(d) Electric heater.

(e) Busbar box.

(f) First-stage drying chamber.

(g) Feed tank.

(h) Pressure-equalising line.

(i) First-stage cyclone.

(j) Rotary valve.

(k) Filter bag.

(l) Second-stage pneumatic dryer.

(m) Second-stage cyclone.

(n) Product receiver.

(o) Intermittent, automatically operated butterfly valve.

(p) Cooler-scrubber.

(q) De-entrainer.

CV Control valve. CV3 is a pneumatically operated valve.

F Flowmeter. F1 and F2 are Pitot tube$, the rest are rotameters.

H Humidity probe. H1 and H2 are LiCl cells; H3 and H4 are wet-and-dry-bulb psychrometer$.

P Pressure tapping.

RV Regulating valve.

TA Air temperature point thermocouples. TA1 & TA2, TA8 & TA9 are wet-and-dry-bulb psychrometers.

TC Temperature controller.

TW Wall temperature point (thermocouples brazen onto wall).

Figure 3 only:

 Drying air, feed or product.

 Service line.

 Control line.

ratio adjusted to give the correct inlet temperature. At the end of this stage a cyclone finally separates out the product, and the air goes to the cooler-scrubber.

For the set-up to work properly, pressure balance between the two stages must be maintained (for example, if the pressure drop through the 1st stage is too low, the hot air would be at low pressure and unable to flow into the 2nd stage). This is obtained by manipulating the valves V1, V2, V3, V4 and especially the butterfly valve V5 (see figure 3). Fine control is given by the control valve CV2.

Figures 4 and 5 are an isometric sketch and a photograph of the set-up (except the blower). For further details on the operating procedures the reader is referred to Appendix C.

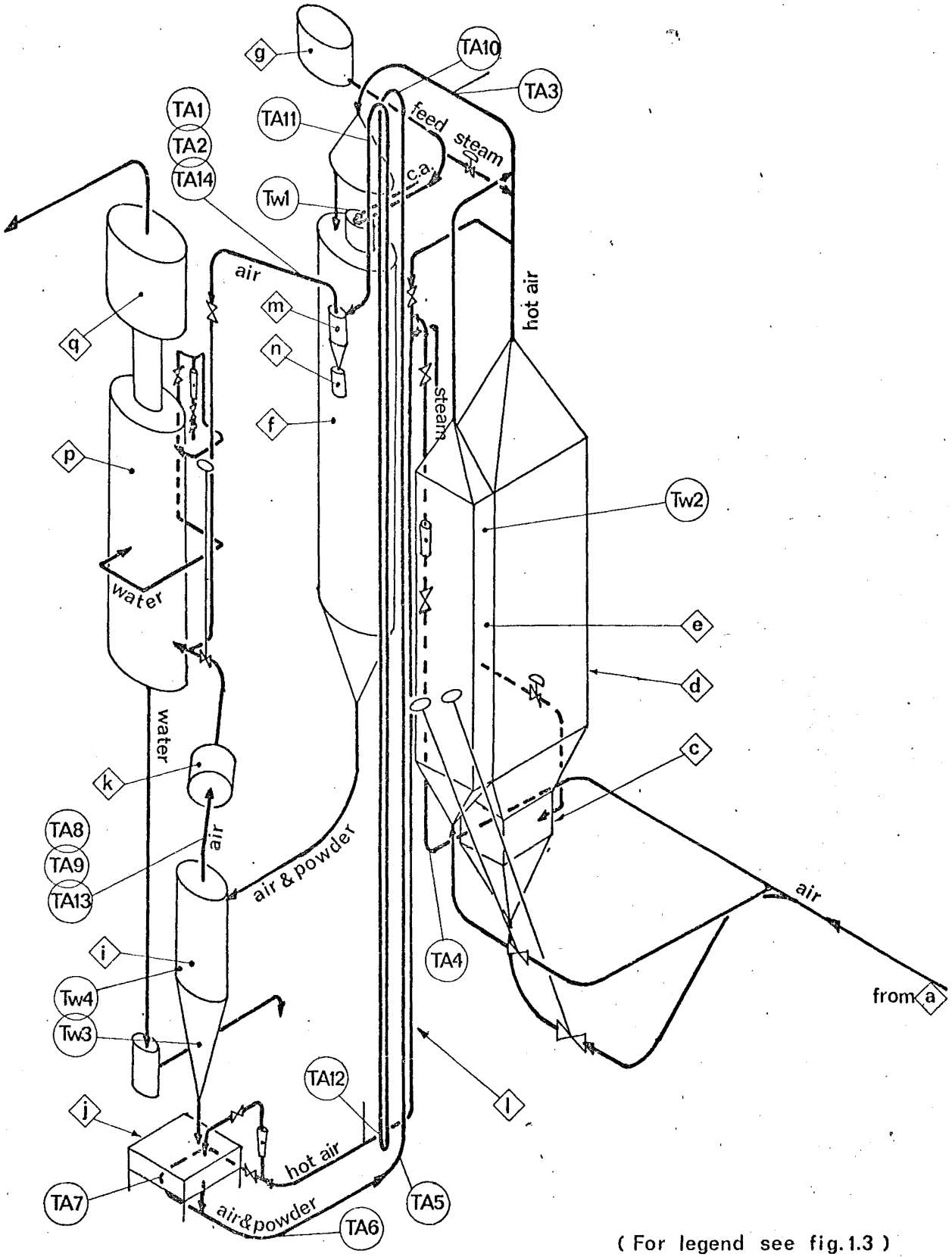
II.2 Individual items

II.2.1 The first-stage drying chamber (figure 6)

The column is 400 mm diameter by 2 m long, with a conical bottom 550 mm long, made of mild steel, later hot dip galvanised. The air inlet, consisting of four elliptical parts surrounding the nozzle, was designed to give easy access to the atomiser, rather than controlled plug flow. In such a design, the sudden expansion of air around the nozzle would give good spray-air mixing at the cost of some backmix being present.

II.2.2 The feed system

In the present work, two pneumatic nozzles with external mixing were used, henceforth referred to as no.1 and no.2 nozzles respectively. Their description and performance characteristics are shown in figure 7 and table 1. The "effective" air-flow areas and the discharge



(For legend see fig.1.3)

FIGURE 1.4 : ISOMETRIC DIAGRAM OF INSTALLATION

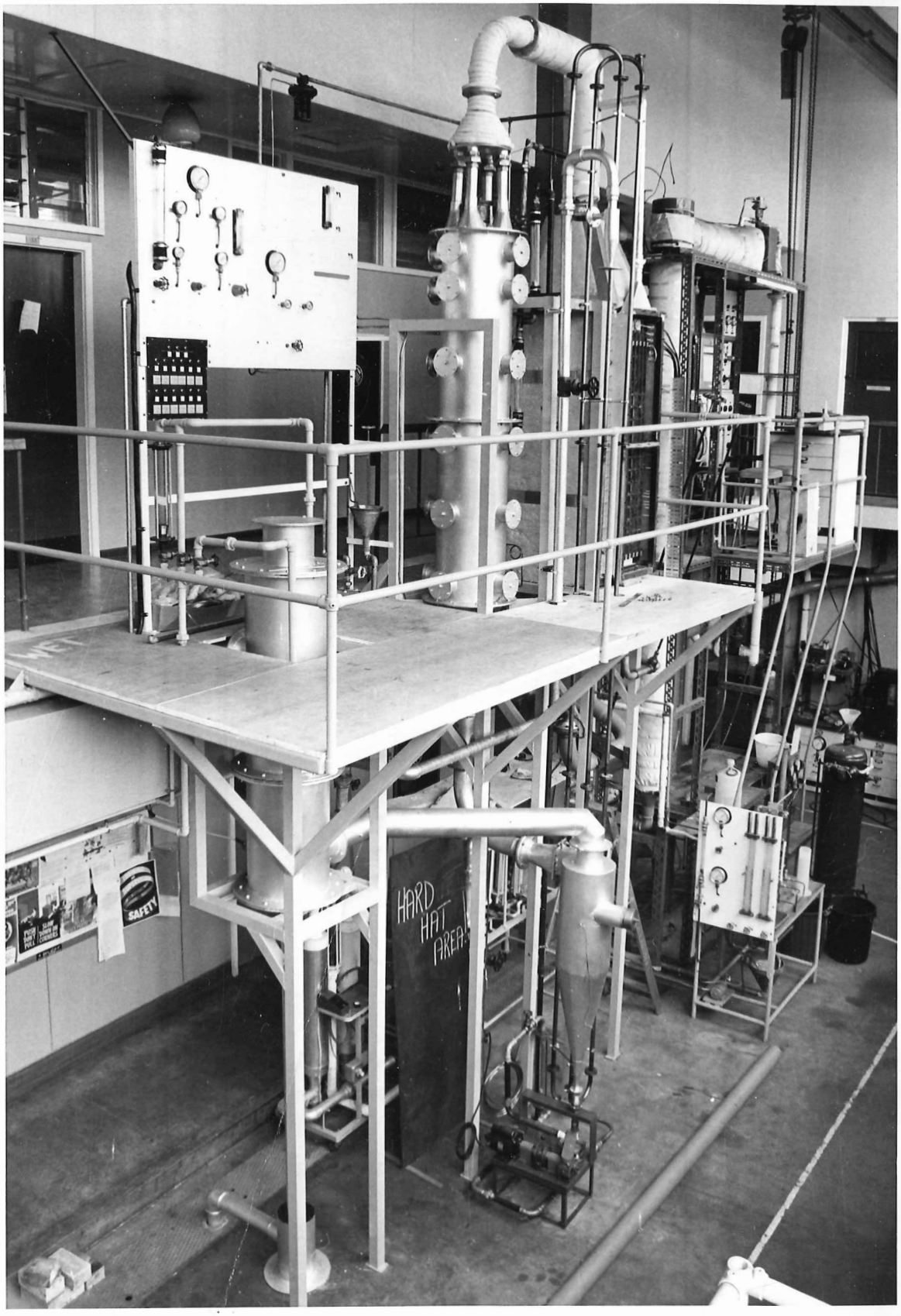
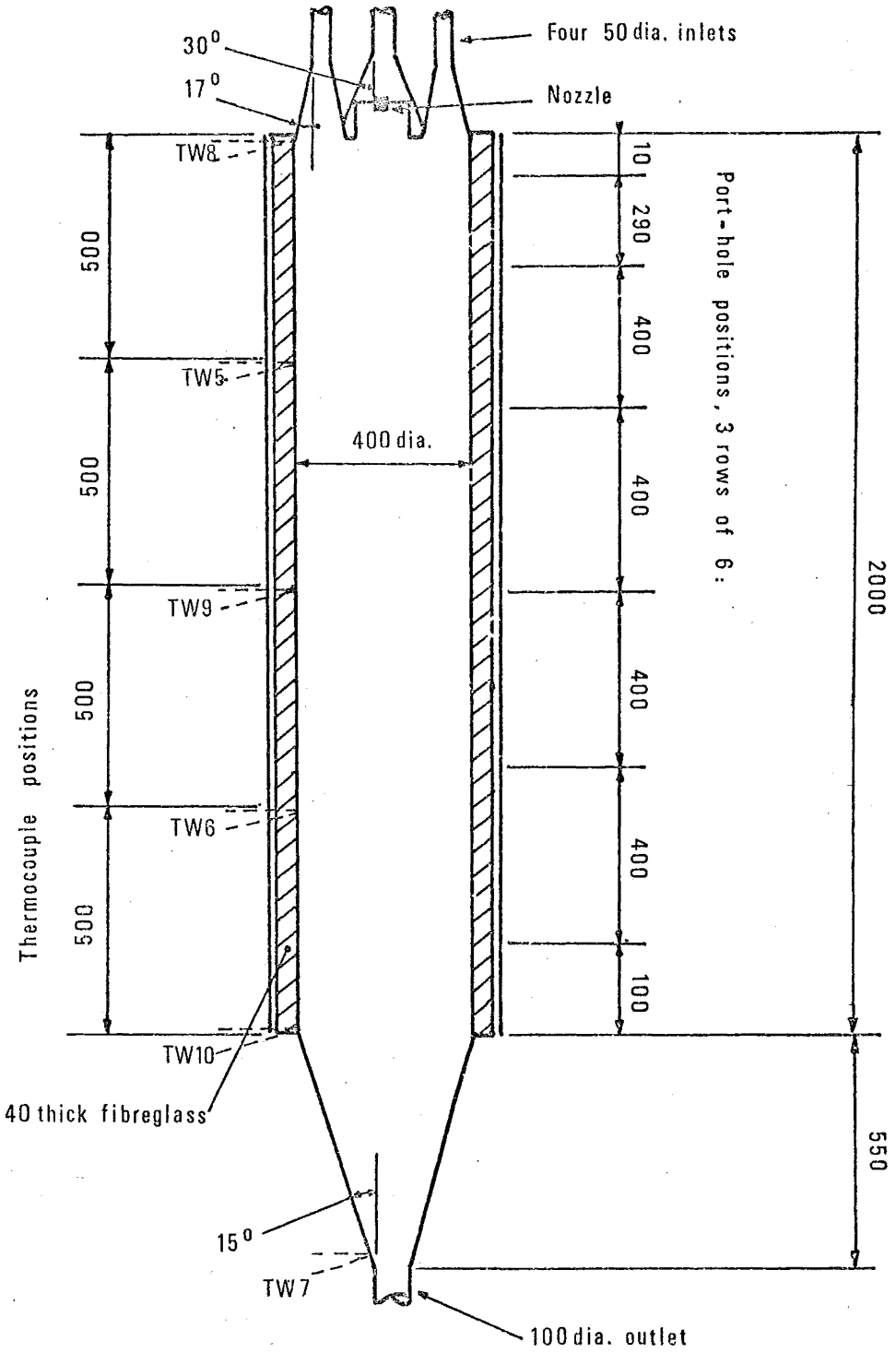


FIGURE 1.5



TW : see fig.1.3

All dimensions in mm

Cross-section area .126 m^2

Volume .274 m^3

FIGURE 1.6: FIRST-STAGE DRYING CHAMBER

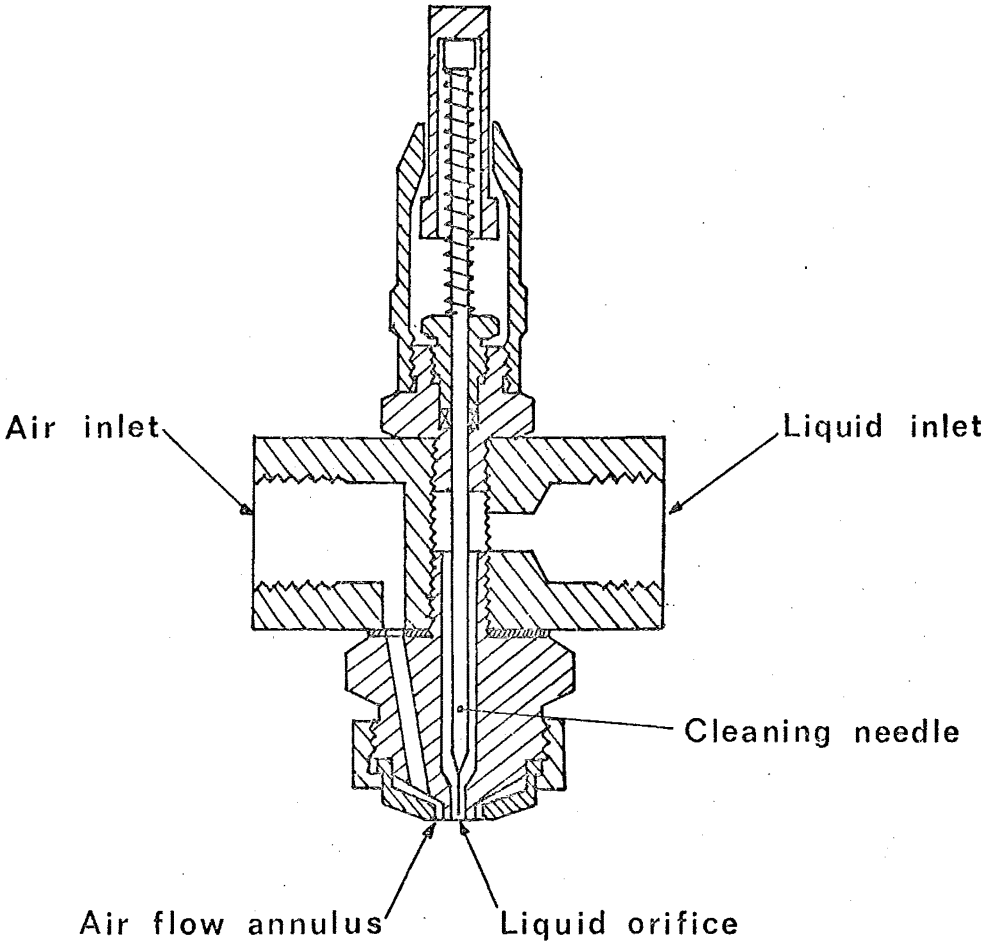


FIGURE 1.7: ATOMISER USED IN THIS WORK

TABLE 1.1

Description and performance characteristic of atomisers used

Identification in this work	No.1	No.2
Manufacturer	Spraying Systems Co. (U.S.A.)	
Type	Pneumatic, round spray, siphon or gravity feed	
Manufacturer's catalog no.	1/4 JCO set-up 1A	1/4 JCO set-up 2
Liquid orifice diameter (nominal)	0.406 mm	0.711 mm
Air annulus inner dia. (nominal)	1.27 mm	1.27 mm
Air annulus outer dia. (nominal)	1.626 mm	1.778 mm
Effective air flow area (measured)	1.4 mm^2	2.3 mm^2
Discharge coefficient (measured)	5.66×10^{-9} kg/s Pa	3.42×10^{-9} kg/s Pa

NB. The discharge coefficient C_N is defined by

$$C_N \equiv \frac{\text{Air mass rate at room temperature}}{\text{Absolute upstream pressure } P_a}$$

$$P_a \geqslant 1.9 \times 10^5 \text{ Pa}$$

(isentropic flow equation)

coefficients were not calculated from the manufacturer's data but determined from discharge experiments (see Appendix B.II).

Initially the liquid was fed under a gravity head of 0 to 600 mm, with the feed container sitting on a movable platform and connected to the column by a pressure equalising line (figure 3). However, this set-up was inadequate to control the flow, so a peristaltic pump (no internal moving part) with variable speed, in series with a restriction valve, were added to the line. When working with slurries, a solenoid-operated cleaning needle clears the orifice regularly with an adjustable period of 1 to 5 seconds, the solenoid circuit being actuated by a small electric motor.

II.2.3 The second-stage dryer

The 2nd stage is a pneumatic dryer 1 inch (25.4 mm) I.D., 18 m long (but can be reduced to 6 m by re-connecting), made of 9 sections of mild steel tubing. The stream flows up 6 m, then either goes to a cyclone or flows into a U-tube for another 12 m before reaching the cyclone. Lagging consists of 25 mm of fibreglass preformed sections.

A major problem in commissioning the plant was the deposition of powder on the walls and especially at the bends, gradually clogging up this pneumatic stage. In fact, industrial practice recommends against such small pipes and tight bends as used in the present equipment (E3, S18). However, after several trials, the following measures were successful in preventing clogging and ensuring a 99% recovery of slightly moist zinc-oxide powder:

(1) The use of glass bends with a 120 mm bend radius;

(2) The use of pneumatic vibrators at the bends with a frequency of about 400 Hz;

(3) Installation of a butterfly valve downstream of the cyclone which opens and closes intermittently with a period of about 2 s. This valve was actuated by an automatically operated solenoid.

II.2.4 The rotary valve

This is an essential piece of equipment in a two-stage installation, transferring the powder from one stream to another. Although several types are commercially available, none would handle small-sized (1 in. inlet/outlet) equipment. Hence a rotary valve was designed and built, with the help of Mr. C. Campbell of this department, to the following criteria:

(1) To be suitable for 1 in. (25.4 mm) diameter inlet/outlet;

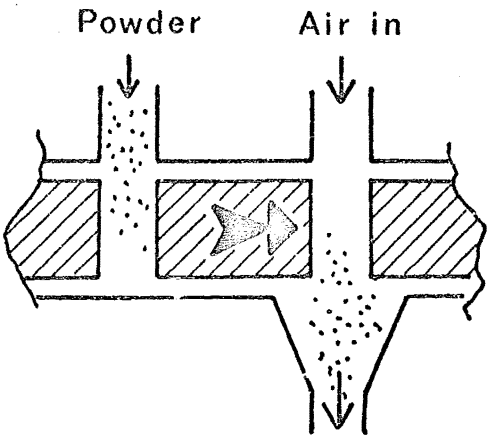
(2) To ensure an even flow of powder, with a minimum of intermittence of discharge;

(3) To reduce hold-up time to a minimum;

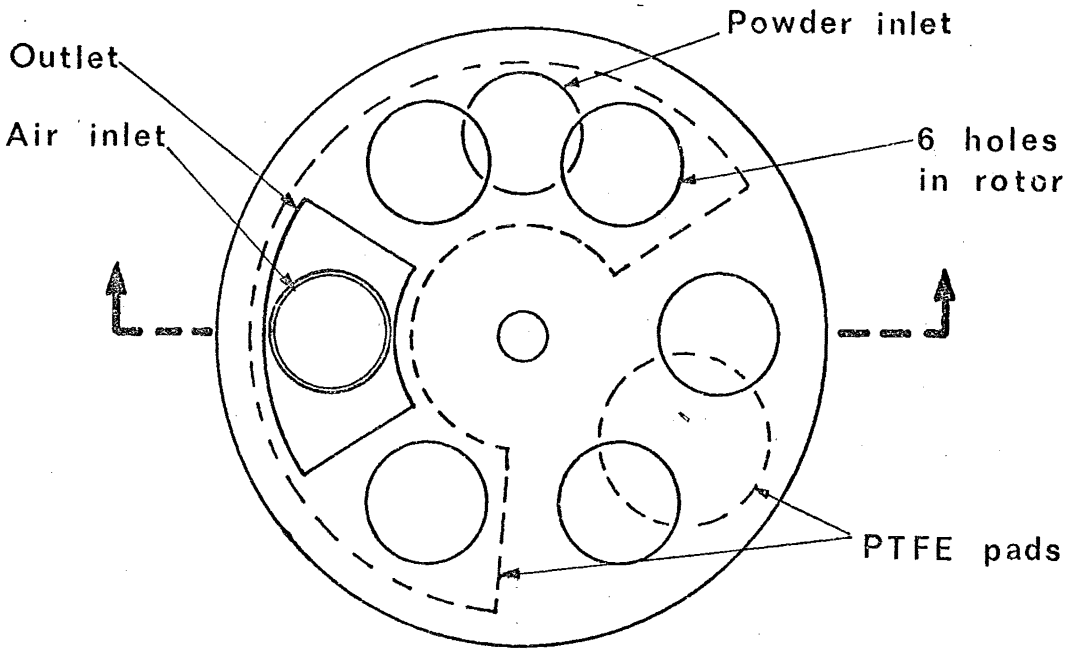
(4) To minimise contact between powder and wall.

The principle of operation and sketch of the valve are shown in figure 8. The rotor, revolving about a vertical axis, contains 6 vertical cylindrical holes 25.4 mm in diameter.

Each hole passes under the inlet, when some powder falls into it, then over the outlet when the powder is blown out under air pressure. The speed of the rotor is adjusted to a value of about 100-120 rpm to ensure that the powder does not reach the bottom of the hole before it is blown out. Sealing was ensured by pads of P.T.F.E. around the holes in the stationary part, and good contact between the P.T.F.E. surfaces and the stainless steel rotor maintained by spring-loading the top of the assembly.



Principle of operation



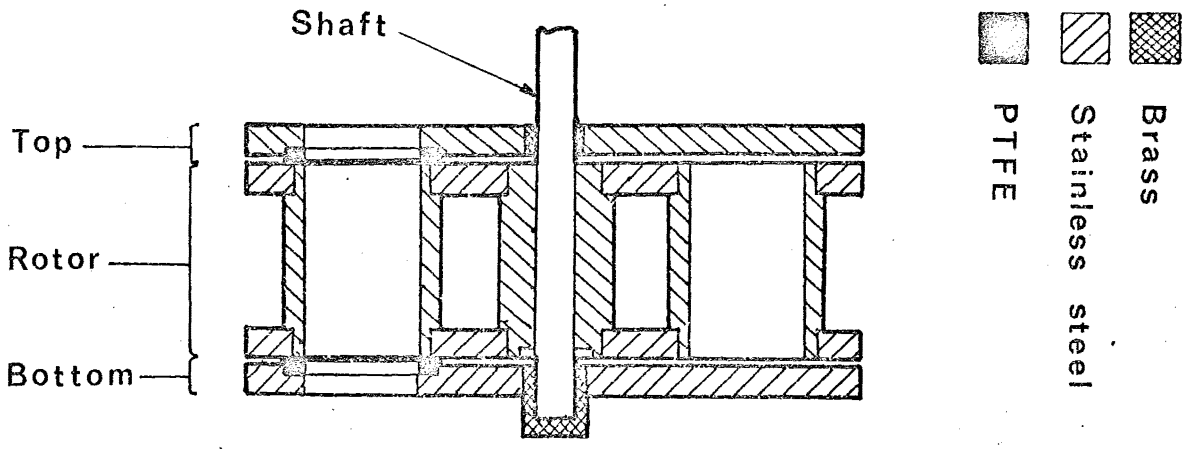


FIGURE 1.8: THE ROTARY VALVE

II.2.5 Powder collection equipment

The product is collected at the outlet of the 1st stage by either of two cyclones (the smaller can be used for air velocities up to 1.5 m/s in the spray dryer, the larger for higher air rates). These cyclones are of Stairmand's "high-efficiency" type (figure 9a), with diameters of 300 mm and 165 mm respectively. A pneumatic vibrator is used to prevent powder build-up on the wall. A 160 mm diameter bag filter can be installed near the cyclone outlet to remove the finer particles.

For the 2nd stage, a 150 mm diameter Stairmand-type cyclone made of glass was used.

The cooler-scrubber (figure 9b) at the end of the air-flow line consists of a 400 mm diameter column with two grid plates which are stacked with Pall rings to a height of 150 mm to increase contact at low air rate. It was designed for a maximum air rate of 0.43 kg/s and a maximum water rate of 2 kg/s (at low air rate).

II.2.6 Air flow, heating, humidifying and temperature control

A Rootes blower with a maximum capacity of 0.56 m^3/s (700 scfm) at 24 kN/m^2 (3.5 psig) was used to generate air flow. A gear-box and bypass system enable the flow to be varied from zero to the maximum flow. On top gear the pulsation frequency of the blower is 24 Hz, on third gear it is 13.5 Hz.

Heating the air is done in two stages: a steam heater (maximum power 49 KW at 480 kPa (70 psig) steam pressure) heats the air up to 115-138°C, then further heating is done by an electric heater with 39 x 1.25 KW elements with mild steel sheaths and fins (maximum allowable temperature: 430°C), installed in 3 banks in a staggered configuration and connected to a 3-phase 220 V power supply.

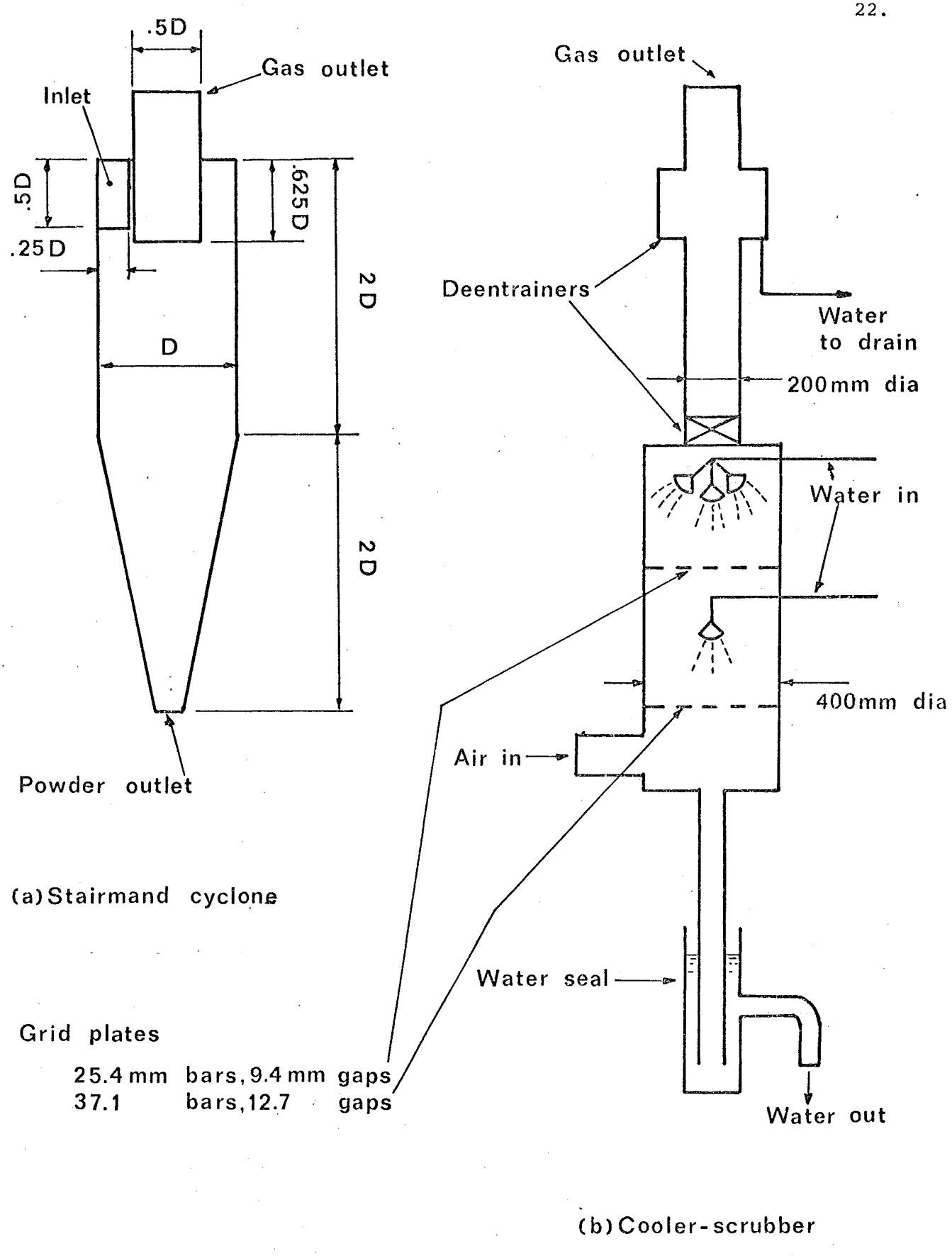


FIGURE 1.9: SEPARATION EQUIPMENT

A flow sensor automatically triggers the switching-off of the current whenever the flow is stopped, and a micro-switch performs the same function whenever the lid of the connection box is opened. The connection box (containing 6 bus bars and small connectors) is cooled with a bypass air stream (figure 3). Groups of 3 elements (one in each phase) can be disconnected at will to adjust the heat input.

Temperature control in the first stage is done by controlling the steam pressure in the steam heater with a pneumatically operated proportional controller and an electrically actuated valve.

The valve has 12.7 mm (½ in.) inlet/outlet and a valve coefficient of $C_v = 4.0$, where C_v is defined as the number of US gpm of water discharged through a wide open valve with a 1 psi pressure drop through it (S17). This arrangement keeps the inlet temperature constant to within ± 1°C.

In the second stage, temperature control is done by varying the cold air stream into this stage with a pneumatic controller and electrically operated valve, the valve having a C_v coefficient of 2.5.

Humidifying steam to the first stage is controlled by a pneumatically actuated valve, but the pneumatic pressure is set manually on a pressure regulator. A globe valve controls humidifying-steam flow to the second stage.

II.3 Monitoring equipment

II.3.1 Flow measurement. Total flow to both stages is measured with a pitot tube placed in the 100 mm (4 in.) diameter inlet line on a long straight section. Flow-profile measurements were done to correlate the velocity along the axis to the mean velocity according to the method outlined in (P6), and results are shown in figure 10. Flow

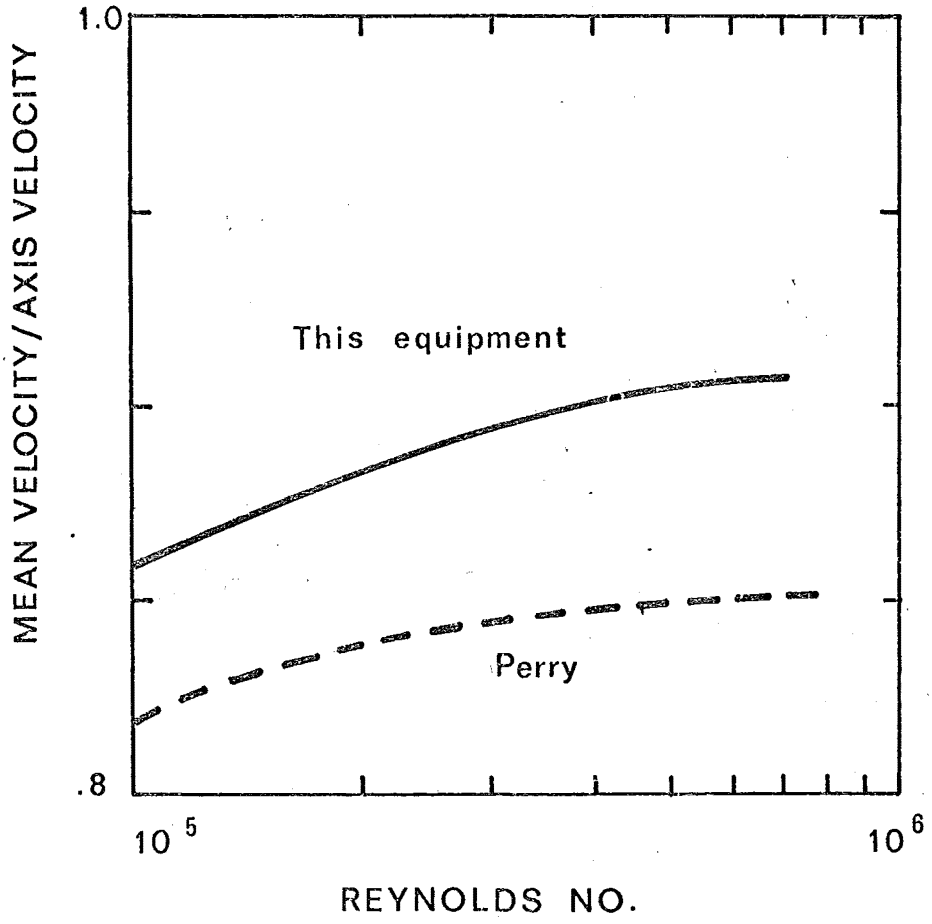


FIGURE 1.10 : MEAN/AXIS VELOCITY RATIO IN 100MM DIAMETER AIR INLET PIPE

through the busbar box is also monitored with a Pitot tube in the 25.4 mm diameter inlet line.

Second-stage air flow, hot and cold, and liquid feed rates are measured with rotameters.

II.3.2 Temperature measurements

Thermometer and (copper-constantan) thermocouple junction positions are shown in figures 4 and 6. For wall-temperature measurements the thermocouples are welded on, while for air-temperature measurements they are placed in a 6 mm I.D. radiation shield and a flow of air is drawn through the shield over the junction (this current of air is also used to measure humidity). A Phillips 12-point recorder with a maximum sensitivity of 2 mV f.s.d. is used to record thermocouple voltages.

II.3.3 Humidity measurements

The humidity of inlet air to each stage is measured with a Lithium-chloride cell [K3] (Phillips type PR 6010 H). This instrument measures directly the dew-point which is related to the absolute humidity of the air. The characteristics of the sensor are shown in table 2.

For the outlet streams, miniature wet-and-dry-bulb psychrometers were specially made, with the advice of Dr. P.E. Doe of Tasmania University (figure 11). Calibration of this instrument was done on a stream of air of known humidity, and the following correction to the indicated wet bulb temperature must be applied:

$$T^*_{sm} - T^*_{st} = 0.06\ (T - T^*_{st}) \pm 15\%$$

where T^*_{sm} and T^*_{st} are the measured and "true" wet-bulb temperatures respectively, and T is the air temperature. The "wet bulb" must be kept clean by frequent washing, for example before each run.

TABLE 1.2

LiCl Dew-point probe characteristics

(Manufacturer's values)

Air temperature range: $-30^{o}C$ to $+ 100^{o}C$

Dew-point range: $-30^{o}C$ to $+ 60^{o}C$

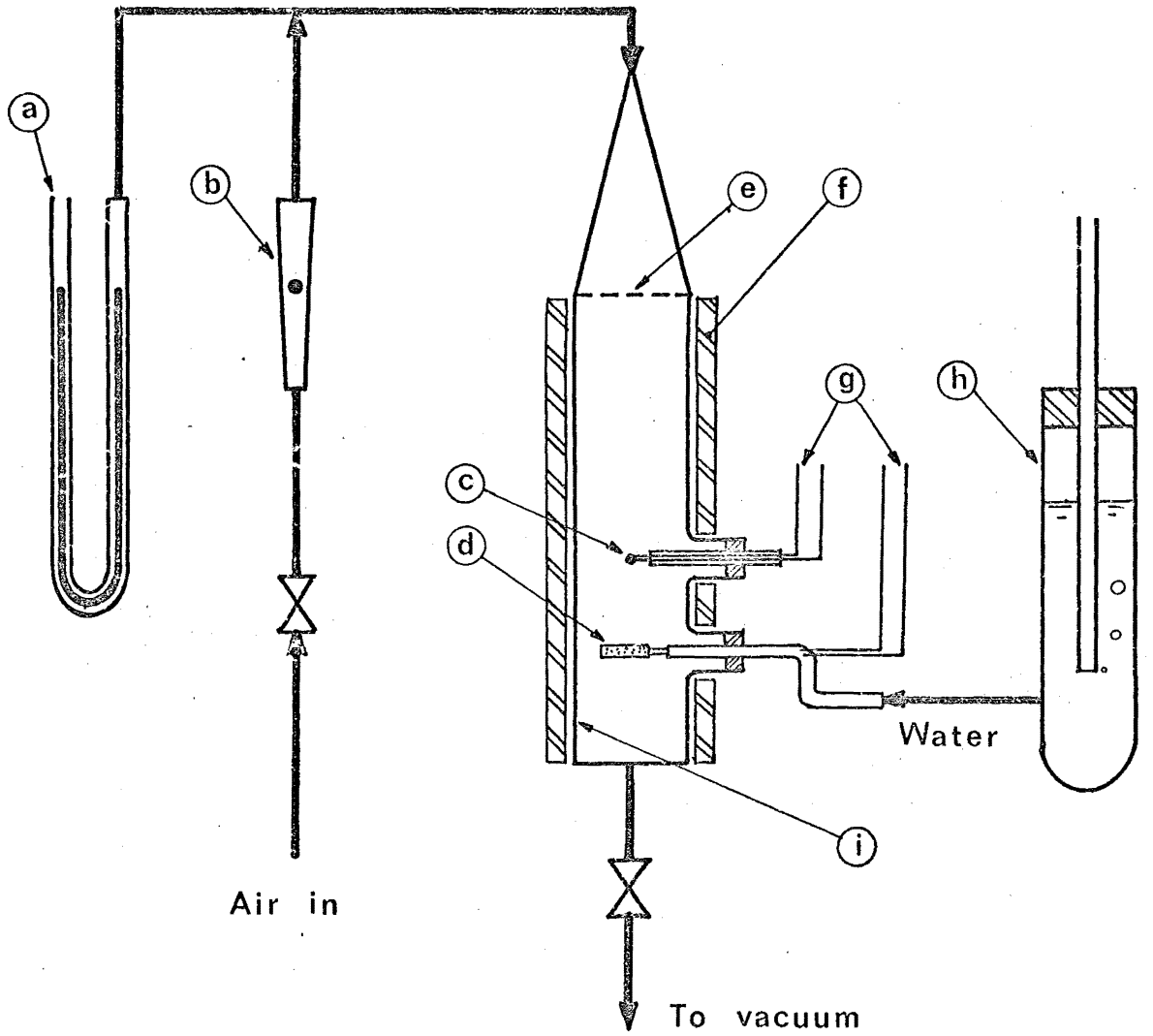
Air velocity: recommended: 0 m/s

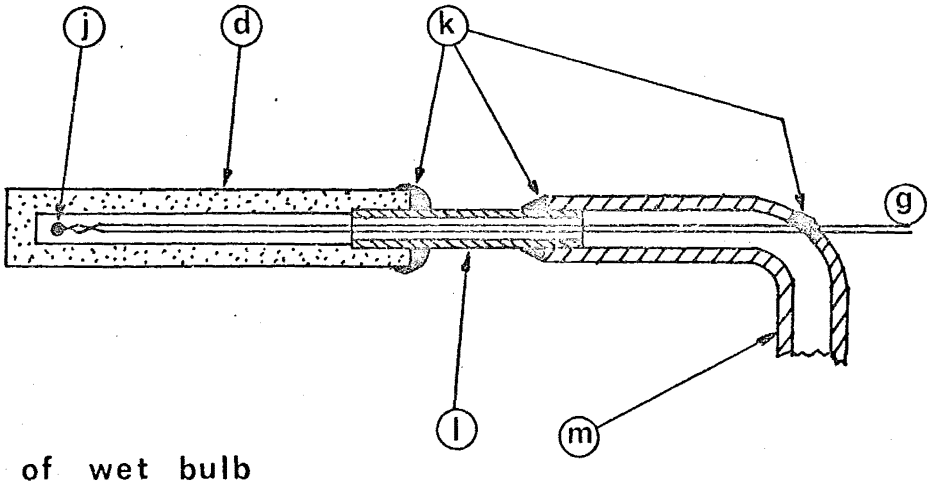
maximum: 0.5 m/s

Accuracy: $\pm 1^{o}C$ Dew-point.

Calibration curve:

Dew-point / ^{o}C	Resistance/Ω
0	113.67
5	116.38
10	119.09
15	121.81
20	124.51
25	127.53
30	130.55
35	133.57
40	136.49
45	138.91
50	141.33
55	143.75
60	146.16





Detail of wet bulb

FIGURE 1.11: PSYCHROMETER

Legend for Figure 1.11

(a) Mercury manometer.

(b) Rotameter.

(c) Dry-bulb thermocouple junction.

(d) Wet-bulb, made of Vyon porous plastic, 3 mm O.D., 1.5 mm I.D., 20 mm long, bonded to drawn glass tubing (l) below under low heat, then glued with Araldite.

(e) Filter gauze.

(f) Aluminium foil - fibreglass - aluminium foil lagging.

(g) 32-gauge (0.274 mm diameter) Copper-Constantan thermocouple wires with fibreglass insulation. For wet-bulb, wires are insulated with varnish.

(h) "Minsky" constant-level water-feed bottle.

(i) Glass tube.

(j) Wet-bulb thermocouple junction.

(k) Araldite glue.

(l) 2 mm O.D. drawn glass tubing.

(m) 4 mm O.D. glass tubing.

CHAPTER 2.

TRACER KINETICS; BACKGROUND AND THEORY

Chapter contents:

III. TRANSFER FUNCTION METHODS

1. Introduction

2. Basic quantities and relationships

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INTRODUCTION

Tracer kinetics provide a method of flow investigation whereby some small quantity of an easily detectable substance is injected into the inlet of a flow system (pipe or vessel) and the concentration monitored at the outlet. In this way information is gained about what is happening inside the system, information which can be used to improve the design and operation of the equipment, to set up an optimal control system, or to predict how the equipment will respond to external manipulations.

The use of tracer kinetics is becoming increasingly popular, one of the reasons being its experimental simplicity. The basic concepts have evolved in the 1950's with the work of Danckwerts (D1), Levenspiel, Bishoff, Avis and others, and have been summarised by Levenspiel (L6, L7). More recent advances have been reviewed elsewhere. (H11,H12,S6,B21)

In this chapter, we shall first describe the basic concepts and methods of tracer kinetics, then develop one class of methods in particular, those involving Laplace Transforms, for use in subsequent work.

I. FUNDAMENTALS OF TRACER KINETICS

I.1 Basic quantities and concepts

I.1.1 Holding time and reduced time.

For the flow of a fluid through a vessel the holding time or space time τ is defined by

$$\tau \equiv V/v \qquad (2.1)$$

where V is the vessel volume and v the volumetric flow rate of the fluid calculated at its inlet density. In subsequent discussion we shall assume the fluid density to be constant, hence τ is also the mean residence time.

The reduced time θ is defined by

$$\theta \equiv t/\tau \quad . \tag{2.2}$$

I.1.2 Age distribution curves

Age distributions can be defined in terms of either θ or t :

(a) The internal age distribution of fluid in the vessel:

$I\, d\theta \equiv$ fraction of fluid inside the vessel having an age (past stay time) between θ and $\theta+d\theta$.

$I_t dt \equiv$ fraction of fluid inside the vessel having an age between t and t+dt.

(b) The exit age distribution, or residence time distribution function (R.T.D.):

$E\, d\theta \equiv$ fraction of fluid in the exit stream having spent a time between θ and $\theta+d\theta$ in the vessel.

$E_t dt$ = fraction of fluid in the exit stream having spent a time between t and t+dt in the vessel.

Since these curves are normalised

$$\int_0^\infty E\, d\theta = \int_0^\infty E_t dt = 1 \tag{2.3}$$

$$\int_0^\infty I\, d\theta = \int_0^\infty I_t dt = 1 \tag{2.4}$$

I.1.3 Ideal response curves

Age distributions are somewhat abstract concepts. In practice information about them can be obtained by injecting a tracer at the inlet of the vessel and measuring the response curve at the outlet. Two idealised injection patterns are useful for theoretical considerations:

(a) The Impulse-response or C-curve

Suppose a δ-pulse is injected at time t = 0, the total amount of tracer used being Δ. Then

$C\, d\theta \equiv$ fraction of Δ present in the exit stream between θ and θ+dθ

$C_t dt \equiv$ fraction of Δ present in the exit stream between t and t+dt .

(b) The step-response or F-curve

Suppose the inlet concentration of tracer is suddenly increased from 0 to c_o. Then

$$F \equiv c/c_o$$

$$F_t \equiv c/c_o$$

where c_o is the concentration of tracer in the exit stream at time t or θ.

The relationships between the dimensional and dimensionless forms of the age distributions and ideal response curves are listed below:

$$E(\theta) = \tau E_t(t) \tag{2.5}$$

$$I(\theta) = \tau I_t(t) \tag{2.6}$$

$$C(\theta) = \tau C_t(t) \tag{2.7}$$

$$F(\theta) = F_t(t) \tag{2.8}$$

where $t = \tau\theta$.

I.1.4 End conditions

Vessels can be open-ended (open) or close-ended (close). In the latter case the flow into and out of the vessel is by bulk movement only, while in the former diffusion can also occur at the inlet and outlet. For example, if the vessel is close-ended, it is clear that C = E. But if it is open-ended, a δ-pulse injection does not result in a δ-pulse inlet concentration; back-diffusion up the inlet

stream occurs and the inlet concentration will be non-zero at $t > 0$. Hence $C \neq E$, and in fact E and I lose their significance because molecules are moving in and out of the vessel more than once.

The following relationships can be proved[L6]:

(a) For all end conditions:

$$F = \int_0^\infty C \, d\theta \quad ; \quad C = \frac{dF}{d\theta} \tag{2.9}$$

(b) For closed vessels:

$$C = E \tag{2.10}$$

$$I + F = 1 \tag{2.11}$$

I.1.5 Moments of the C-curve

The first moment of the C-curve is defined by

$$M_1 = \bar{\theta} \equiv \int_0^\infty C\theta \, d\theta \tag{2.12}$$

$$M_{t1} = \bar{t} \equiv \int_0^\infty C_t \, t \, dt \tag{2.13}$$

hence $\bar{\theta} = \bar{t}/\tau$ (2.14)

The second moment with respect to the time origin is defined by:

$$M_2' \equiv \int_0^\infty C \, \theta^2 \, d\theta \tag{2.15}$$

$$M_{t2}' \equiv \int_0^\infty C_t \, t^2 \, dt \tag{2.16}$$

hence

$$M_2' = (M_{t2}')^2/\tau^2 \tag{2.17}$$

The second moment can also be defined with respect to the first, in which case it is a measure of the spread of the C-curve:

$$M_2 = \sigma^2 \equiv \int_o^\infty C(\theta-\bar{\theta})^2 \, d\theta \tag{2.18}$$

$$M_{t2} = \sigma_t^2 \equiv \int_o^\infty C_t(t-\bar{t})^2 \, dt \tag{2.19}$$

hence

$$\sigma^2 = \sigma_t^2/\tau^2 \tag{2.20}$$

$$\sigma^2 = M_2' - \bar{\theta}^2 \tag{2.21}$$

For closed vessels

$$\bar{\theta} = 1 \tag{2.22}$$

or $$\bar{t} = \tau \tag{2.23}$$

For open vessels this will not necessarily be so; because of diffusion at the inlet and/or outlet, the effective volume holding the tracer will include elements in the inlet and/or outlet lines, and will be greater than the actual vessel volume, so that

$$\bar{\theta} > 1$$

or $$\bar{t} > \tau \quad .$$

I.1.6 Transfer Functions

By the convolution theorem (Kl2), any system with linear properties (i.e. where the total response to several stimuli is equal to the sum of the responses to each) will have a characteristic transfer function

$$\mathcal{J}(s) \equiv \bar{c}_o(s) \; / \; \bar{c}_i(s) \tag{2.24}$$

where $\bar{c}_o(s)$ is the Laplace Transform of the outlet stream tracer concentration, and $\bar{c}_i(s)$ that of the inlet stream concentration. s is the Laplace-transform parameter.

Since the Laplace transform of the δ-pulse is 1 for all s, we have for close-ended systems:

$$\mathcal{J}(s) = \bar{C}_t(s) = \bar{C}(\tau s) \quad . \tag{2.25}$$

From its definition[K12],

$$\bar{f}(s) \equiv \int_{-\infty}^{\infty} f(t) \exp(-ts)\, dt \quad , \tag{2.26}$$

it can be seen that the Laplace transform is a moment-generating function, i.e.

$$M'_{tk} = (-1)^k \mathcal{J}^{(k)}(0) \tag{2.27}$$

where M'_{tk} is the k-th moment of the C_t-curve with respect to the origin. This provides a convenient method for calculating these moments even when the C-curve cannot be explicitly expressed[V1]. Equation 27 holds strictly for closed vessels only. For open vessels the left-hand side must be replaced by the difference in the k-th moments of the outlet and inlet concentration curves.

I.1.7 Frequency response and Fourier transforms

The response of a linear system to a sinusoidal input is characterised by an amplitude ratio A and a phase-lag angle ψ, both functions of the frequency ω.

$A(\omega)$ and $\psi(\omega)$ can be found directly using sinusoidal inputs. More conveniently they can be found either from data or from theory by the equation

$$\mathcal{J}(i\omega) = A \exp(-i\psi) \tag{2.28}$$

where $\mathcal{J}(i\omega)$ is the Laplace transform with the imaginary argument iω, or Fourier-transform transfer function, and $i = \sqrt{-1}$.

A useful property of the Fourier transform is that a further Fourier transformation gives back the original function:

$$\text{if} \quad Y(\omega) = \int_{-\infty}^{\infty} z(t)\ \exp(i\omega t)dt$$

$$\text{then} \quad z(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} y(\omega)\ \exp(-i\omega t)dt \qquad (2.29)$$

Hence the C-curve can be obtained from the frequency response. This property is used in the deconvolution of the response curve, where the response to a random pulse is used to calculate the frequency response and from this the C-curve [C4].

I.2 Flow modeling

I.2.1 Basic components of flow modeling

In modeling a flow system one usually constructs a network of basic units, the most common of which are described below:

(a) The stirred tank or backmix vessel: this is the "most mixed" flow unit, characterised by a uniform concentration of tracer in the whole vessel. It is a one-parameter model, with the parameter τ.

(b) The plug-flow vessel: this is the "least mixed" flow unit, also a single parameter model characterised by τ. The flow in it is parallel without backmix. All molecules in the exit stream have spent exactly τ seconds in the vessel.

(c) The axially-dispersed plug-flow vessel (ADPF): the flow is subject to axial dispersion of Fick's law type:

$$u\frac{\partial c_A}{\partial x} + \frac{\partial c_A}{\partial t} - \mathcal{D}\frac{\partial^2 c_A}{\partial x^2} = 0 \qquad (2.30)$$

where c_A is any concentration, u the fluid mean velocity, x the axial distance and $\mathcal{D}$ the dispersion coefficient.

In dimensionless terms

$$\frac{\partial c_A}{\partial \xi} + \frac{\partial c_A}{\partial \theta} - \frac{1}{Pe}\frac{\partial^2 c_A}{\partial \xi^2} = 0 \qquad (2.31)$$

where

$\xi = x/L$

$\theta = ut/L = t/\tau$

$Pe = uL/\mathfrak{D}$

and L is the vessel length.

This model is intermediate between the previous two (which are its extreme cases). It is characterised by two parameters, τ and Pe. Its behaviour further depends on end conditions and has been the subject of a large amount of work.(A6, B11, B12, L5, P7, T3, V1, O1)

(d) Deadwater: deadwater occupies vessel space, but does not participate in the flow, hence it reduces the effective volume and the first moment of the C-curve:

$$\bar{t} < \tau$$

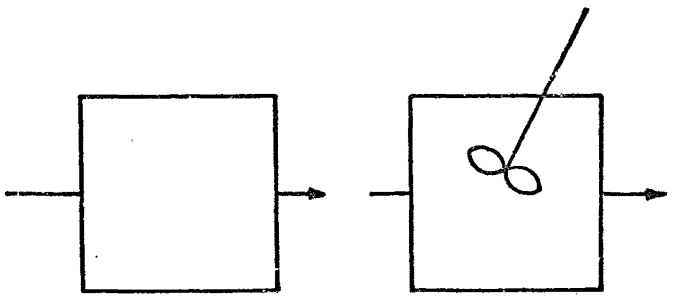
$$\bar{\theta} < 1 .$$

In some recent work(B21), the slow mass interchange between the deadwater region and the rest of the system has been studied.

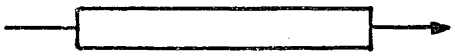
The symbols for these flow units are shown in figure 1, and the properties of the first three in Table 1.

I.2.2 Mixed models

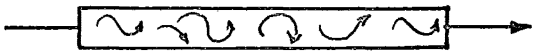
An example of a mixed model is shown in figure 1(e). The properties of a composite model can be deduced from those of elementary units according to the rules laid out in Table 2. In this table f_j is the fraction of fluid entering the j-th stream in a parallel flow network. M'_{tk} is the k-th moment with respect to the origin.



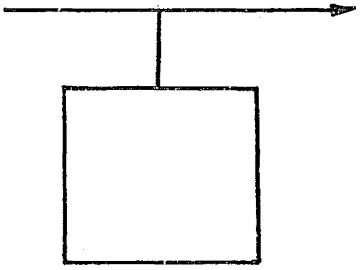
(a)Stirred tanks



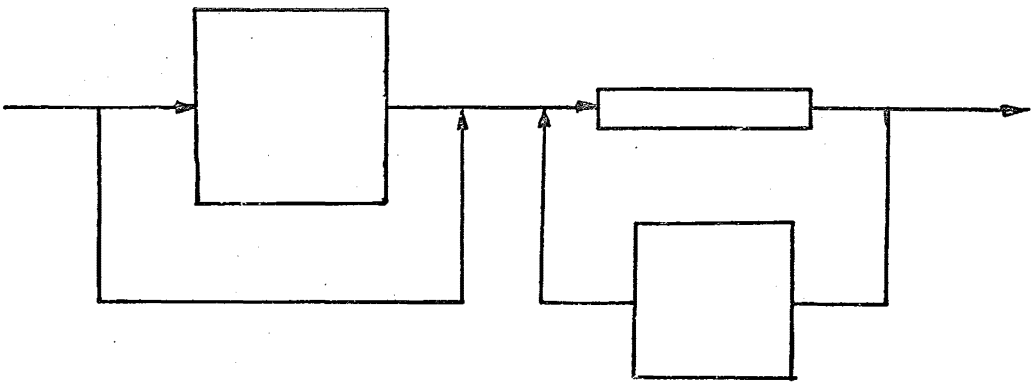
(b)Plug-flow



(c) Axially dispersed plug-flow



(d)Deadwater



(e)A mixed model

FIGURE 2.1: SYMBOLS OF FLOW MODELS

TABLE 2.1

Properties of the elementary flow units

1. Stirred tank:

$$F = 1 - I = 1 - \exp(-\theta) \tag{2.32}$$

$$C = E = \exp(-\theta) \tag{2.33}$$

$$\bar{\theta} = 1 \tag{2.34}$$

$$\sigma^2 = 1 \tag{2.35}$$

$$\mathcal{J}(s) = 1/(1+\tau s) \tag{2.36}$$

$$A = 1/\sqrt{1 + \tau^2\omega^2} \tag{2.37}$$

$$\tan \psi = - \tau\omega \tag{2.38}$$

2. Plug flow:

$$F = 1 - I = H(1) \quad \text{where H = unit step function} \tag{2.39}$$

$$C = E = \delta(1), \text{ the unit pulse} \tag{2.40}$$

$$\bar{\theta} = 1 \tag{2.41}$$

$$\sigma^2 = 0 \tag{2.42}$$

$$\mathcal{J}(s) = \exp(-\tau s) \tag{2.43}$$

$$A = 1 \tag{2.44}$$

$$\psi = - \tau\omega \tag{2.45}$$

(continued)

TABLE 2.1 (continued)

3. A.D.P.F.:

(a) open-ended vessel:

$$C = \frac{1}{2}\sqrt{\frac{Pe}{\pi\theta}}\exp\left\{-\frac{Pe(1-\theta)^2}{4\theta}\right\} \tag{2.46}$$

$$\bar{\theta} = 1 + 2/Pe \tag{2.47}$$

$$\sigma^2 = 2/Pe + 8/Pe^2 \tag{2.48}$$

$$\Delta\sigma^2 = 2/Pe \tag{2.48b}$$

$$\mathcal{F}(s) = \exp\left\{\frac{Pe}{2}\left(1 - \sqrt{1 + \frac{4\tau s}{Pe}}\right)\right\} \tag{2.49}$$

$$A = \exp\left\{\frac{Pe}{2}\left(1 - \sqrt{\frac{a+1}{2}}\right)\right\} \tag{2.50}$$

$$\psi = -\frac{Pe}{2}\sqrt{\frac{a-1}{2}} \tag{2.51}$$

where $a = \sqrt{1 + (4\tau\omega/Pe)^2}$

(b) close-ended vessels:

$$\bar{\theta} = 1 \tag{2.52}$$

$$\sigma^2 = 2/Pe - 2\{1 - \exp(-Pe)\} / Pe^2 \tag{2.53}$$

$$\mathcal{F}(s) = \frac{2b\exp\{Pe(1+b)/2\}}{b-1 + (b+1)\exp(bPe)} \tag{2.54}$$

where $b = \sqrt{1 + 4\tau s/Pe}$

(c) open-closed or closed-open vessel:

$$\bar{\theta} = 1 + Pe \tag{2.55}$$

$$\sigma^2 = 2/Pe + 3/Pe^2 \tag{2.56}$$

See Reference (V1) for further properties.

TABLE 2.2

Rules for calculating the properties of mixed models

	Closed vessels in parallel	Closed vessels in series
(a) E, C curves	$C = \sum_j f_j C_j$	$C = \int_{-\infty}^{\theta} C_1 (\xi-\theta) C_2(\xi) d\xi$
(b) Moments	$M'_{tk} = \sum_j f_j M'_{tkj}$	$\bar{t} = \sum_j \bar{t}_j$ $\sigma_j^2 = \sum_j \sigma_{tj}^2$
(c) Transfer functions	$\mathcal{J}(s) = \sum_j f_j \mathcal{J}_j(s)$	$\mathcal{J}(s) = \prod_j \mathcal{J}_j(s)$
(d) Frequency response	-	$A = \prod_j A_j$ $\psi = \sum_j \psi_j$

I.2.3 Stochastic models

In some systems the flow may switch repeatedly from one pattern to another. Such non-stationary behaviour is frequently caused by turbulence, when eddies detach from obstacles or flows separate from boundaries.

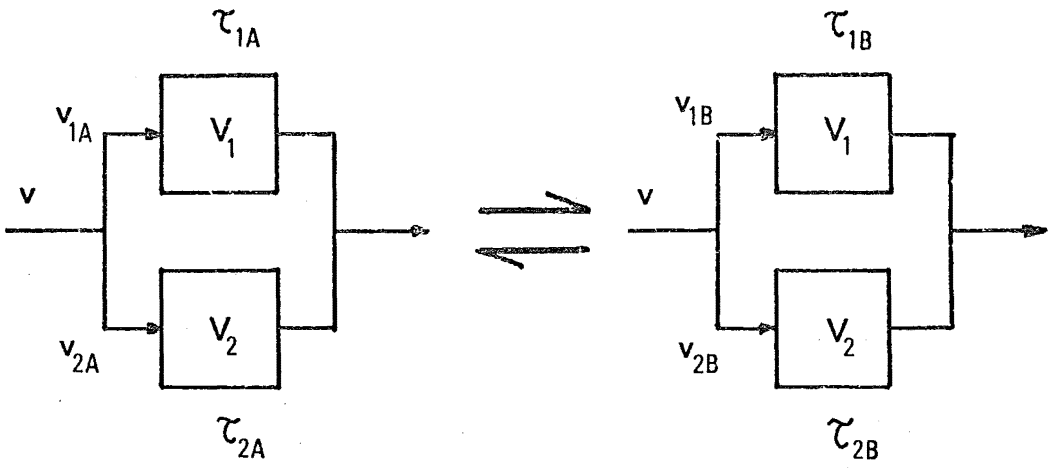
Krambeck et al.[K10, S6] introduced the concept of stochastic models to deal with non-stationary flows. Their models assume a network of tanks, each with a given volume, interconnected by flows which can take certain sets of values or "states" (say A, B ...), each state having a constant (ergodic) probability, say α, β... (fig.2a).

For such models the C-curves will change from experiment to experiment, unless the switching rate is infinitely fast. If we average out a large number of experimental C-curves, the result will be the same as that of an "equivalent" deterministic model where the flow is split into several parallel streams, a fraction α of the flow going to the configuration corresponding to state A, and so on (fig. 2b).

The difference between the stochastic model and the equivalent deterministic model is however shown up in the spread of the C-curve values at each instant in time, which is a function of the switching rate and the fluctuation magnitude. At the moment this subject is still at an embryonic stage.

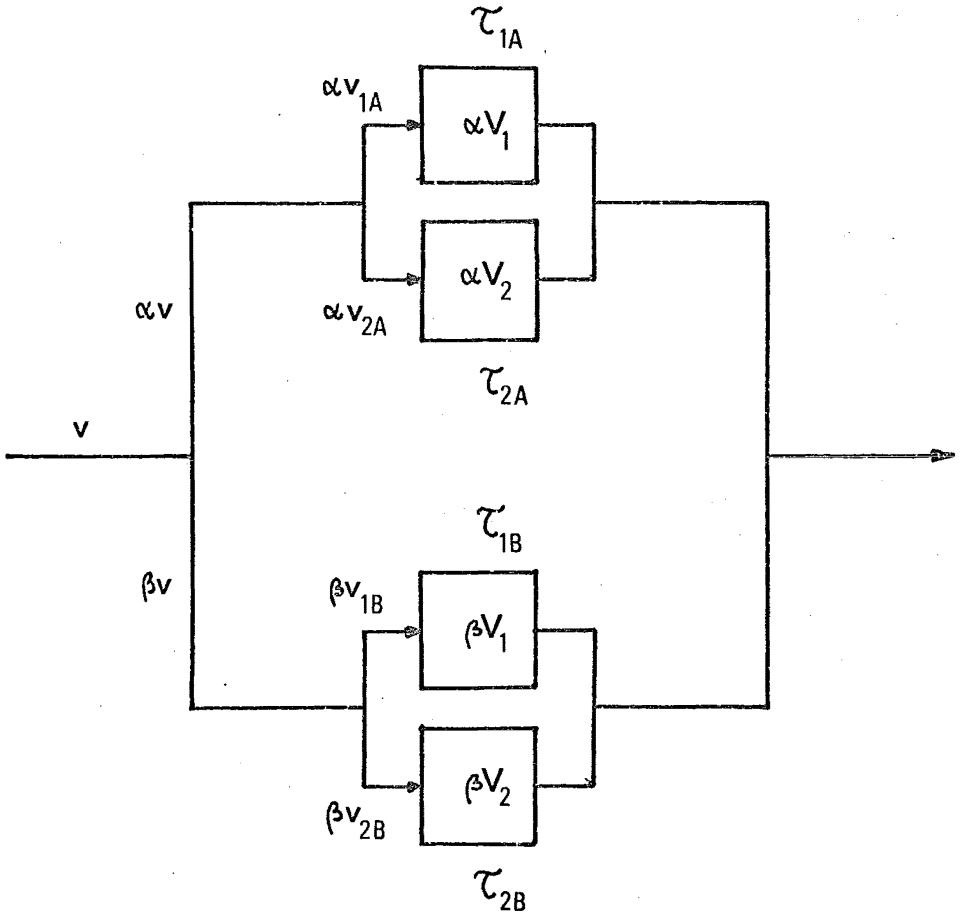
I.3 Flow patterns, mixedness and conversion

The residence time distribution by itself is insufficient to characterise a flow system; the mixedness must also be specified. The degree and scale of mixedness are closely related to the flow pattern.



State A , probability α State B , probability β

(a) Stochastic model



(b) Deterministic model

FIGURE 2.2 : A STOCHASTIC MODEL AND ITS DETERMINISTIC EQUIVALENT

A system will have the maximum degree of mixedness for a given R.T.D. if molecules that have the same life expectation in the vessel will mix with each other as early as possible[Z1]. Two systems with the same R.T.D. but different flow patterns (hence different degrees of mixing) are shown in figure 3.

Where the scale of mixedness is concerned the system may be macromixed or micromixed. A macromixed fluid (or macrofluid) flows as large aggregates (compared to molecular size), each retaining its own identity - for example, swarms of non-interacting particles, droplets or bubbles. In a micromixed fluid, on the other hand, molecules mingle with each other and lose their identities[D2].

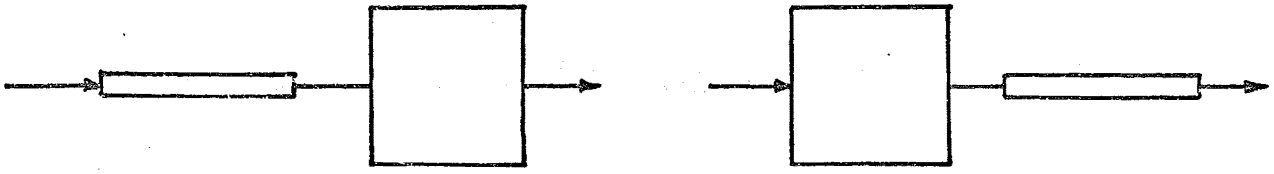
The conversion of chemical reactions depends on both the degrees and scale of mixedness[L6]. For reaction with order smaller than unity, the conversion is least with macromixing and minimum mixedness. For reactions with order larger than unity, the effect is reversed. Only when the order is one (linear reaction) is the conversion independent of the mixedness and the flow pattern.

A macrofluid can be said also to have a minimum degree of mixedness. The conversion in a macromixed system is independent of the flow pattern and is given by

$$X = \int_0^\infty X_b \, E_t \, dt \qquad (2.57)$$

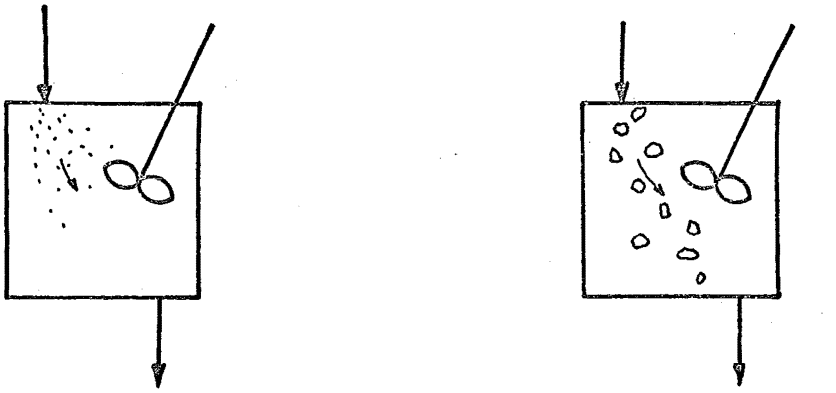
where X is the fraction of initial reactant remaining in the outlet stream, and X_b the fraction of reactant remaining at time t in a batch reactor.

Most tracer experiments will provide information on residence-time distributions, but not on mixedness or flow patterns. The foregoing considerations point to the limitations of such methods.



Lesser mixedness Greater mixedness

(a) Degree of mixedness



Micromixed fluid Macromixed fluid

(b) Scale of mixedness

FIGURE 2.3: MIXEDNESS

II. EXPERIMENTAL MODELING AND PARAMETER FINDING METHODS

In a tracer kinetics experiment the tracer must first be injected in any of several ways, then the data obtained must be processed in some way. Thus a two-way classification of methods suggests itself (Table 3).

II.1 Methods of tracer injection

II.1.1 Delta-pulse input: When possible this is the most desirable type of input. From a time-domain point of view, its zero spread enables an accurate measurement of the spread due to the system itself to be made. From a frequency-domain point of view, a delta-pulse has a large content of all frequencies, thus enabling a large range of ω to be investigated. Its disadvantages are that it may disturb the flow, and is difficult to administer.

The result of a delta-pulse input is a directly-obtained C-curve, on which a direct curve-fit in the time domain against a theoretical C-curve, an analysis of moments, or a Laplace-transform analysis can be performed. Alternatively it can be Fourier-transformed and undergo a frequency analysis, a quick and economical procedure if fast Fourier transformations are used (W6). Finally an integration will give the F-curve, hence all methods applicable to the F-curve can also be used here.

II.1.2 Step input: Step inputs do not give as much information as pulse inputs, but in some particular cases they may be useful alternatives (see section II.2.5).

II.1.3 Sinusoidal input: although this type of input gives the frequency response directly, it is time-consuming and difficult to perform, hence it is little used in practice.

II.1.4 Random or imperfect pulse input: This is the next best thing to the delta-pulse. It is easy to administer and is probably the most widely used method of injection. Moment analysis and Laplace transform methods are readily applicable to the data obtained. Frequency analysis can also be done after a Fourier transformation has given the amplitude ratios and phase angles. Curve fits to theoretical models can be done in the time domain, either before deconvolution or after (the deconvolution being achieved by a double Fourier transform).

The pulse must be measured both at the inlet and at the outlet. It should be kept as narrow as possible for the reasons already outlined (section II.1.1).

II.1.5 Injection of reactants: This is a recent development[P1] whereby a reactant with order different from unity is injected either as a steady stream or as a pulse, and the outlet concentration measured. This method can discriminate between several flow patterns or degrees of mixedness for a given R.T.D. . Parimi and Harris [P1] used it successfully to distinguish between the two flow patterns shown in figure 3(a). They also stated that a pulse input gives better discrimination than a steady injection. Data processing was by curve-fit in the time domain.

TABLE 2.3

Classification of tracer kinetics methods

Tracer input:	Data processing: Moments analysis	Frequency analysis	Laplace Transform	Time domain curve fit
δ-pulse	Y	Y	Y	Y
Step input	N	Y	Y	Y
Sine input	N	Y	Y	N
Random pulse	Y	Y	Y	Y
Reactants	N	N	N	Y

Y : possible combination

N : impossible combination.

II.2 Methods of processing the response data

II.2.1 Analysis of moments (L6)

The moments of a C-curve or the differences in the moments of the input and output curves are usually expressible in terms of the model parameters (see for example Table 1). Hence by comparing the experimental moments to the theoretical ones, these parameters can be evaluated. Although simple to apply, the method of moments suffers from several disadvantages:

(1) There is no guarantee that the model used is valid.

(2) If the response curve has a long tail, large errors will be involved in calculating the higher moments. Levenspiel (L6) suggested cutting off the tail at $t=3\tau$. Jagota et al. (J1) proposed an iterative tail-cutting technique. Neither method has much theoretical justification.

(3) Because of the errors involved in the higher moments it is inadvisable to go beyond the second moment, hence models with more than 2 parameters cannot usually be evaluated.

II.2.2 Frequency analysis

For some of the simple systems the frequency response follows simple equations which enable the parameters to be found graphically. For example, in the case of the two-tanks-in-series (second order) model it can be shown that

$$(\tan \psi) = -(T_1 + T_2)\omega \tag{2.58}$$

$$\left(\frac{1}{A^2} - 1\right)\frac{1}{\omega^2} = (T_1^2 + T_2^2)\,\omega^2 + (T_1^2 + T_2^2) \tag{2.59}$$

where T_1 and T_2 are the holding times of the tanks.

These two equations can be plotted as straight lines, the slopes and intercepts of which then give T_1 and T_2 after some manipulation.

Similarly, the the single-tank-and-plug model:

$$\frac{1}{A^2} = 1 + T_t^2\,\omega^2 \tag{2.60}$$

where T_t is the space time of the tank.

For the n-equal-tanks-in-series model:

$$\frac{d(\omega^2)}{d(\ell nA)} = -\left(\frac{2}{n}\right)\omega^2 = \frac{2n}{\tau^2} \tag{2.61}$$

where τ is the total space time.

For the axial dispersion model with open ends (see Table 1):

$$\ell nA = \frac{Pe}{2} + \left(\frac{Pe\,\tau}{2}\right)\left(\frac{\omega}{\psi}\right) . \tag{2.62}$$

A more orthodox and generally useful method, and one widely used in automatic control works, is to perform a curve-fit in the frequency domain[C4]. From Parseval's theorem (see for example Ref.(D4)), it can be shown that a curve-fit, by minimisation of squared errors in the frequency domain, is equivalent to a similar procedure in the time domain:

$$\int_0^\infty \left| \mathcal{F}_t(i\omega) - \mathcal{F}_e(i\omega) \right|^2 d\omega = \pi \int_0^\infty \left[C_{tt}(t) - C_{te}(t) \right]^2 dt \qquad (2.63)$$

where $\mathcal{F}_t(i\omega)$ and $\mathcal{F}_e(i\omega)$ are the theoretical and experimental Fourier-transform transfer functions, and $C_{tt}(t)$ and $C_{te}(t)$ are the theoretical and experimental C_t curves respectively. By minimising the left-hand side with a numerical procedure, the right-hand side is also minimised.

Although very flexible, this method, like any other curve-fit, does not guarantee the validity of the model. Any number of model parameters can be introduced but one cannot be sure that these parameters have any physical meaning.

II.2.3 Methods using Laplace Transform Transfer functions

Conceivably a theoretical L.T. Transfer function can be curve-fitted to the experimental one, as is done for the Fourier-transform transfer function. In practice this has not been done because no relationship has yet been found between the errors in the L.T. domain and those in the time domain[H11].

Recently, Michelsen and Østergaard [M12, M13, O1] introduced methods whereby the Transfer function and its derivatives are manipulated to enable the parameters of the axially dispersed plug flow model to be found graphically. As the author has applied these methods to other models for use in subsequent parts of this work, they will be the subject of the third part of this chapter.

II.2.4 Curve-fitting in the time domain

The response to any non-periodic input can be fitted to a model curve by an error minimisation procedure [R9]. Although very flexible, this method does not guarantee the validity of the model and this must be confirmed by other means. If an inordinate number of parameters are used, the hill-climbing procedure may end up at local minima which are quite far from the true minimum error. In general no more than 5 or 6 parameters should be used, although a 12-parameter model has been curve-fitted elsewhere on a counter-current spray dryer, without very much success [B9].

II.2.5 Miscellaneous methods

For some simple models the C or F curves follow simple equations from which the parameters can be found graphically. For example, $\ell n\ C_t$ or $\ell n\ (1-F_t)$ for a single tank can be plotted against time (equations 32, 33) to give a straight line with slope $-1/\tau$.

For the ADPF with large Pe, the C_t-curve tends to a normal distribution with mean $\bar{t}$ and standard deviation σ_t. Hence the F-curve can be plotted on probability graph paper, $\bar{t}$ and σ_t calculated, and τ and Pe deduced [L6].

III. RESPONSE-CURVE PROCESSING BY TRANSFER FUNCTIONS

III.1 Introduction

The use of transfer functions with a real argument offers many attractive features:

(1) Laplace transforms have been used extensively in other fields, and comprehensive reviews and tables are available for consultation.

(2) Experimental transfer functions can be obtained from almost any type of tracer injection, provided the inlet concentration curve is known.

(3) The Laplace transform weights down the response curve by a factor exp(-st), which tends to zero as t tends to infinity. Hence tailing effects, which account for large errors in many cases, are reduced. This offers a definite advantage over, say, the method of moments.

(4) The Laplace transformation is an integration procedure which tends to average out fast random fluctuations, so that only the main features of the response curve remain.

(5) In addition, the approach followed here involves a graphic procedure which enables the validity of the model to be evaluated, something which is not possible in curve-fitting procedures or moment analysis. In transfer-function methods, a valid model shows up as a straight line on a graph.

On the debit side, transfer-function methods as described here are not as flexible as curve-fitting methods. Only methods with no more than 3 or 4 parameters can be evaluated. For the relatively simple situation arising in the present work (Chapter 1) this is not a serious restriction.

For these reasons, transfer-function methods, which were originally introduced by Michelsen and Østergaard [M12, M13, O1] to treat the ADPF, will be generalised for use with several other models of interest to the present work. One of these was specially developed to account for gradual change in the turbulent mixing pattern. Only the graphical version of those authors' method will be followed, for the reasons already mentioned.

III.2 Basic quantities and relationships

III.2.1 Definitions

From now on the non-normalised transfer function $\mathcal{F}^*(s)$ will be used. It is defined by:

$$\mathcal{F}^*(s) \equiv K\, \bar{C}_o(s) \,/\, \bar{C}_i(s) \tag{2.64}$$

where K is an arbitrary proportionality constant. Its introduction facilitates the experimental procedure, as in many practical situations only the relative change in the tracer concentration and not its absolute value can be measured.

The following three functions were introduced by Michelsen and Østergaard:

$$U_o \equiv \ln \mathcal{F}^* = \ln \mathcal{F} + \ln K \tag{2.65}$$

$$U_1 \equiv -U_o' = -\mathcal{F}' / \mathcal{F} \tag{2.66}$$

$$U_2 \equiv -U_1' = \mathcal{F}'' / \mathcal{F} - (\mathcal{F}' / \mathcal{F})^2 \tag{2.67}$$

where ' denotes a derivative with respect to s. The asterisk has been dispensed with in equations 66 and 67 because the constant K drops out during differentiation.

III.2.2 Calculation of the U-functions

U_o, U_1, U_2 are functions of s. If a theoretical model is being considered, they can be derived directly from the theoretical function via equations 65 to 67.

If they are to be found from experimental data, numerical differentiation can be avoided by the use of the following relationships[M12], which can be proved by substituting the defining equation of the transfer function into 65, 66, 67:

$$U_o = [\ln \{ \mathcal{M}_{o_o}(s) \}]_i^o \tag{2.68}$$

$$U_1 = \left[\frac{\mathcal{M}_1(s)}{\mathcal{M}_o(s)}\right]_i^o \tag{2.69}$$

$$U_2 = \left[\frac{\mathcal{M}_2(s)}{\mathcal{M}_o(s)} - \left\{\frac{\mathcal{M}_1(s)}{\mathcal{M}_o(s)}\right\}^2\right]_i^o \tag{2.70}$$

where $[\ ]_i^o$ denotes the difference between the vessel outlet and inlet values, and $\mathcal{M}_{o_n}(s)$ is the n-th moment of the weighted concentration curve:

$$\mathcal{M}_{o_n}(s) \equiv \int_0^\infty c_A \exp(-st).t^n.dt \tag{2.70b}$$

where c_A is the tracer concentration in arbitrary units.

III.2.3 Properties of the U-functions

From equations 68 to 70, some insight into the significance of the U-functions can be gained. When s = 0, $\mathcal{M}_{o_n}(0)$ is the (unnormalised) n-th moment of the concentration curve with respect to the origin. Hence $U_o(0)$ is the logarithm of the ratio of the areas under the inlet and outlet concentration curves respectively, $U_1(0)$ the difference between the mean response times (or first moments) of these concentration curves, and $U_2(0)$ the difference between the variances of these concentration curves:

$$U_1(0) = \bar{t}_o - \bar{t}_1 \tag{2.71}$$

$$U_2(0) = \sigma_{to}^2 - \sigma_{ti}^2 \quad . \tag{2.72}$$

For closed vessels,

$$U_1(0) = \bar{t} \tag{2.73}$$

$$U_2(0) = \sigma_t^2 \tag{2.74}$$

where $\bar{t}$ and σ_t^2 are the moments of the C_t-curve. Equations 71 to 74 are also useful for the analysis of moments.

From the properties of the transfer function (Table 2), it can be shown that the U-functions of a system of closed vessels in series are the sums of the individual U-functions:

$$U_o = \sum_j U_{oj} \tag{2.75}$$

$$U_1 = \sum_j U_{1j} \tag{2.76}$$

$$U_2 = \sum_j U_{2j} \quad . \tag{2.77}$$

For example, the addition of a plug-flow element $[\mathcal{J}(s) = \exp(-T_p s)]$ to a system will contribute a further term $(-T_p s)$ to U_o, a term T_p to U_1, but will not affect U_2.

III.3 Application of transfer function methods to particular cases

III.3.1 ADPF model:[M13]

From equation 49 for the transfer function of the ADPF with open ends, one obtains:

$$U_o = \frac{Pe}{2}\left(1 - \sqrt{1 + \frac{4s\tau}{Pe}}\right) + \ell n\, K \tag{2.78}$$

$$U_1 = \frac{\tau}{\sqrt{1 + 4s\tau/Pe}} \tag{2.79}$$

from which

$$\frac{1}{U_1^2} = \frac{4}{\tau Pe} \cdot s + \frac{1}{\tau^2} \quad . \tag{2.80}$$

Thus, if the model is valid, $1/U_1^2$ when plotted against s will give a straight line, and τ and Pe can be calculated from its slope and its intercept.

Michelsen and Østergaard made a noise sensitivity analysis for this model. If the errors are randomly distributed on both sides of the response curve and if the mean fluctuation amplitude does not

change with time, then the recommended range of s_T values to minimise the errors in Pe should be in the vicinity of 1. However, the choice of s-values must obviously depend on the situation: if, for example, there is some uncertainty in the base line and tailing effects are serious, then larger values of s_T should be used.

III.3.2 Tanks-in-series-and-plug-flow model (figure 4b)

The A.D.P.F. model assumes an equal degree of dispersion or backmix throughout the vessel. Another situation may arise whereby all the backmixing takes place in one part of the vessel (say the entrance zone), while for the remainder plug flow dominates. In this case the model shown in figure 4(b) is applicable.

The equal-tanks-in-series by itself is a common substitute for the A.D.P.F. For a given total tank time T_t the degree of backmixing varies inversely with the number n of tanks:

$$\sigma_t^2 = \frac{T_t^2}{n} \tag{2.81}$$

The C-curve for the present model is given by:

$$C_t = \frac{n^n}{T_t^n \Gamma(n)} (t-T_p)^{n-1} \exp[-n(t-T_p)/T_t] \tag{2.82}$$

where Γ is the gamma function.

The transfer function is given by:

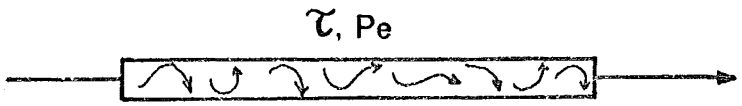
$$\mathcal{J}^*(s) = \frac{K \exp(-T_p s)}{(1+T_t s/n)^n} \tag{2.83}$$

from which

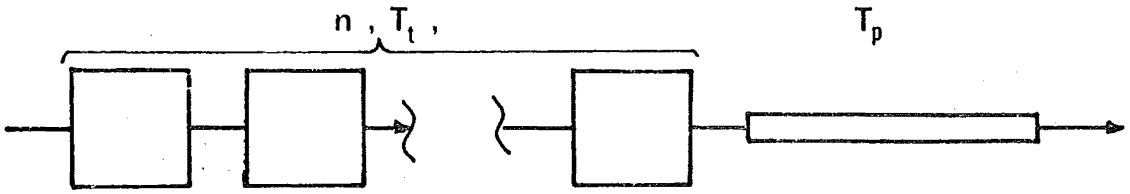
$$U_o = - n \ln(1+T_t s/n) - T_p s + \ln K \tag{2.84}$$

$$U_1 = \frac{n}{n/T_t + s} + T_p \tag{2.85}$$

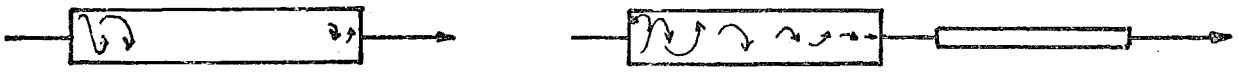
$$U_2 = \frac{n}{(n/T_t+s)^2} \tag{2.86}$$



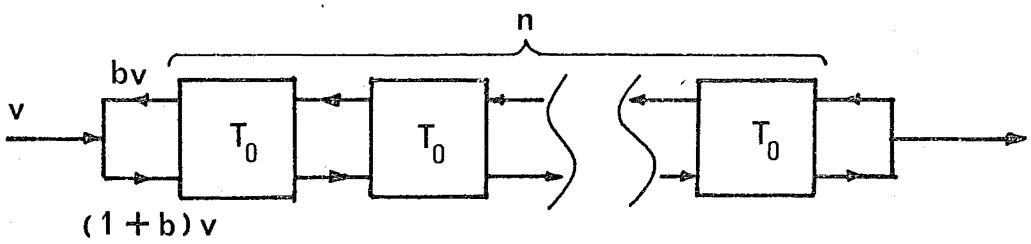
(a) A.D.P.F.



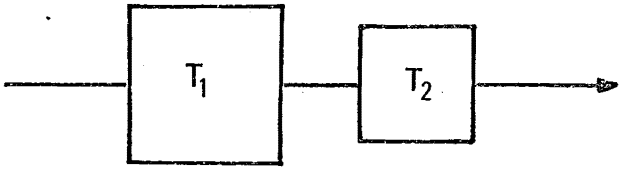
(b) Tanks in series & plug-flow



(c) Diminishing backmix flow



(d) Backflow cells



(e) Second-order system

FIGURE 2.4: MODELS STUDIED BY TRANSFER FUNCTION METHODS

Since this is a three-parameter model, at least two equations must be plotted to find T_t, T_p and n . From equation 85 and 86 one gets:

$$\frac{1}{\sqrt{U_2}} = \frac{\sqrt{n}}{T_t} + \frac{s}{\sqrt{n}} = Y_1 + S_1 s \tag{2.87}$$

$$\frac{U_1}{\sqrt{U_2}} = \sqrt{n}\ (1 + \frac{T_p}{T_t}) + (\frac{T_p}{\sqrt{n}})\ s = Y_2 + S_2 s \tag{2.88}$$

These equations give two slopes (S_1, S_2) and two intercepts (Y_1 , Y_2) for calculating three quantities. There is thus a redundancy which can provide a further check on the validity of the model. For example, a possible combination may be:

$$n = 1/S_1^{\,2} \tag{2.89}$$

$$T_t = 1/(S_1 Y_1) \tag{2.90}$$

$$T_p = S_2/S_1 \tag{2.91}$$

$$= Y_2/Y_1 - 1/(S_1 Y_1) \tag{2.92}$$

III.3.3 Diminishing backmix model

III.3.3.1 Construction of the model

The previous model assumes that the flow changes suddenly from a backmix regime to a plug-flow regime. It is desirable to have an alternative model whereby the degree of backmixing gradually decreases, and such a model will now be constructed.

We first consider a series of tanks, the sizes of which decrease in a geometric series (figure 5).

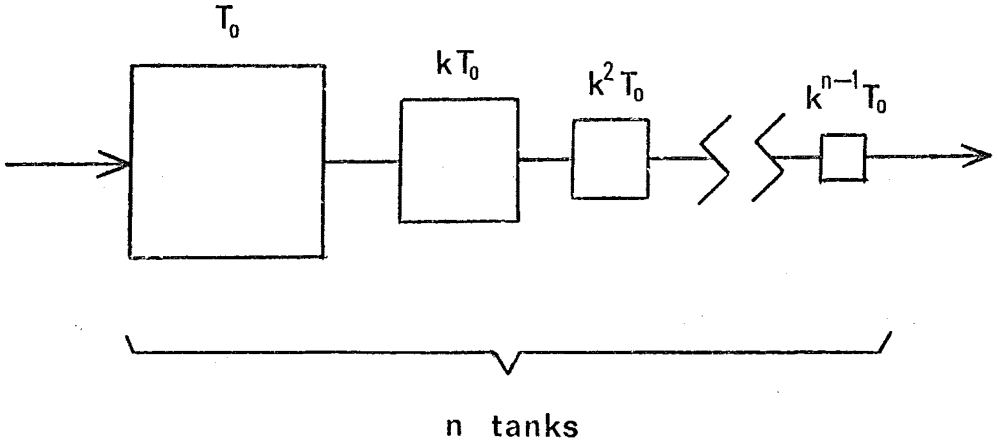


FIGURE 2.5: SERIES OF DIMINISHING TANKS

The transfer- and U-functions of this system are:

$$\mathcal{J}^*(s) = K \prod_{j=0}^{n-1} \frac{1}{1 + k^j T_o s} \tag{2.93}$$

$$U_o = \ell n\, K + \sum_{j=0}^{n-1} \ell n(1+k^j T_o s) \tag{2.94}$$

$$U_1 = T_o \sum_{j=0}^{n-1} \frac{k^j}{1+k^j T_o s} \tag{2.95}$$

$$U_2 = T_o^2 \sum_{j=0}^{n-1} \frac{k^{2j}}{1+k^j T_o s} \tag{2.96}$$

where T_o is the holding time of the first tank, n the number of tanks and k the ratio between successive tank times.

By analogy with equations 94 to 96 the diminishing backmix model will now be defined by the following equations:

$$U_o = \int_o^n \ln(1 + k^z T_o s)\, dz + \ln K \tag{2.97}$$

$$U_1 = T_o \int_o^n \frac{k^z}{1+k^z T_o s}\, dz$$

$$= -\frac{1}{s \ln k} \ln \left(\frac{1+T_o s}{1+T_o k^n s} \right) \tag{2.98}$$

$$U_2 = T_o^2 \int_o^n \frac{k^{2z}}{1+k^z T_o s}\, dz$$

$$= \frac{T_o(k^n - 1)}{s \ln k (1+T_o s)(1+T_o k^n s)} + \frac{1}{s^2 \ln k} \ln \left(\frac{1+T_o k^n s}{1+T_o s} \right) \tag{2.99}$$

III.3.3.2 Properties of the model:

For the present model U_o, $\mathfrak{F}(s)$ and the C-curve cannot be expressed algebraically. T_o, k and n have lost their original meaning in figure 5, but are still measures of the original degree of backmixing, the rate of decrease of backmixing and the total vessel size respectively.

This model is close-ended and the holding time τ is equal to the first moment $\bar{t}$ of the C-curve:

$$\tau = \bar{t} = U_1(0)$$

$$= \frac{T_o(1-k^n)}{-\ln k} \tag{2.100}$$

by taking the limit of equation 98 as $s \to 0$.

The maximum possible value of τ or $\bar{t}$ is obtained by letting $n \to \infty$:

$$\tau_m = \bar{t}_m = \frac{T_o}{-\ln k} \tag{2.101}$$

The variance of the C-curve is

$$\sigma_t^2 = U_2(0) = \frac{T_o^2(1-k^{2n})}{-2\,\ell nk} \qquad (2.102)$$

$$\sigma^2 = \sigma_t^2/\tau^2 = \frac{-\ell nk.(1+k^n)}{2(1-k^n)} \qquad (2.103)$$

As $n \to \infty$, $\sigma^2 \to -(\ell nk)/2$.

III.3.3.3 Parameter finding

Two cases will be considered: in the first one, the end of the vessel is reached while there is still some backmixing; in the second one, backmixing decreases to zero with the last part of the vessel occupied by plug flow.

(a) No plug-flow zone (figure 4(c1))

U_o, U_1, U_2 are given by equations 97 to 99. This is a three-parameter model (T_o, k, n). From 98 and 99:

$$\left[\left(s + \frac{1}{T_o}\right)(U_1 - sU_2)\right]^{-1} = \left(\frac{-\ell nk}{1-k^n}\right) - \left(\frac{T_o k^n \ell nk}{1-k^n}\right) s \qquad (2.104)$$

T_o can be adjusted until equation 104 gives the best straight line, then k and n can be estimated from the slope and the intercept of the plot.

(b) Decreasing backmix zone followed by plug-flow (figure 4c2)

The U-functions can be found by letting $n \to \infty$ in equations 97 to 99 and adding a term for the plug-flow part:

$$U_o = -\int_0^\infty \ell n\ (1 + k^n T_o s)\ dn - T_p s + \ell nk \qquad (2.105)$$

$$U_1 = \frac{-\ \ell n(1+T_o s)}{s\ \ell n\ k} + T_p \qquad (2.106)$$

$$U_2 = \frac{-\ \ell n(1+T_o s)}{s^2\ \ell n\ k} - \frac{T_o}{s\ \ell n\ k\ .\ (1+T_o s)} \qquad (2.107)$$

U_o can also be written as the integral of U_1 , in the form:

$$U_o = \frac{1}{\ell nk}\int_0^{T_o s} \frac{\ell n(z+k)}{z} dz - T_p s + \ell n\ k \qquad (2.108)$$

The integral is the dilogarithmic function, which has been investigated and tabulated elsewhere[A4].

This is again a three-parameter model (T_o, k, T_p). The parameters can be found by plotting

$$\frac{1}{U_1 - T_p - sU_2} = (-\ell nk)s - \frac{\ell nk}{T_o} \qquad (2.109)$$

(an equation obtained by combining 106 and 107), with various T_p, until the best straight line is obtained, then calculate k and T_o from the slope and the intercept. A first estimate of T_p is easily obtainable by visual examination of the response curve.

III.3.4 Backflow cell model (Figure 4d)

This model consists of a series of equal-size stirred tanks with backward as well as forward flow. It has been used to represent the behaviour of systems wherein mixing occurs as a result of turbulent eddying, such as packed beds[S3]. Its established properties are listed below:

$$\bar{t} = \tau = n\,T_o \tag{2.110}$$

where n is the number of cells and T_o the holding time per cell for all passes (i.e. the cell volume divided by the net flow through the system)

$$\sigma^2 = \sigma_t^2/\tau^2 = \frac{1+2b}{n} - \frac{2b(1+b)\left[1-\left(\frac{b}{1+b}\right)^n\right]}{n^2} \tag{2.111}$$

where b is the backward flow rate as a fraction of the net flow rate into (or out of) the system.

For $n \gg 1$,

$$\sigma^2 \simeq \frac{1+2b}{n} \quad . \tag{2.112}$$

The transfer function, neglecting recycling effects at the inlet, is given by:

$$\mathcal{F}^*(s) = K\left\{\frac{1}{2b}\left(1 + 2b + T_o s - \sqrt{1 + 2T_o s(1+2b) + T_o^2 s^2}\right)\right\}^n \tag{2.113}$$

from which

$$U_o = \ell nK + n\ell n(1+2b+T_o s - \sqrt{1 + 2T_o s(1+2b) + T_o^2 s^2}) - n\,\ell n(2b) \tag{2.114}$$

$$U_1 = \frac{n\,T_o}{\sqrt{1 + 2(1+2b)\,T_o s + T_o^2 s^2}} \tag{2.115}$$

$$U_2 = \frac{n\,T_o^2(1+2b+T_o s)}{(1 + 2(1+2b)\,T_o s + T_o^2 s^2)^{3/2}} \tag{2.116}$$

After rearrangement, equations 115 and 116 give:

$$\frac{U_2}{U_1^3} = \frac{s}{n^2} + \frac{1+2b}{T_o n^2} \tag{2.117}$$

$$\frac{1}{U_1^2}\left(1 - \frac{U_2 s}{U_1}\right) = \left(\frac{1+2b}{T_o n^2}\right) s + \frac{1}{T_o n^2} \tag{2.118}$$

which can be plotted for parameter finding in the usual manner.

Note the redundancy (two slopes plus two intercepts, three unknowns)

which allows the validity of the model to be checked as in the case of the tanks-in-series-and-plug-flow model.

The model can be extended to include a plug flow T_p in series. Equations 117 and 118 can still be used to find the parameters, except that U_1 must be replaced by $(U_1 - T_p)$ where T_p is adjusted to give the best straight lines.

III.3.5 Second-order model (figure 4e)

This model, consisting of two stirred tanks in series (with holding times T_1 and T_2 respectively), is frequently mentioned in the literature, especially in the field of automatic control, and will be studied briefly here. It can be shown that:

$$\mathcal{J}^*(s) = \frac{K}{(T_1 s+1)\ (T_2 s+1)} \tag{2.119}$$

$$U_o = \ell n(T_1 s+1) - \ell n(T_2 s+1) + \ell nK \tag{2.120}$$

$$U_1 = \frac{T_1}{1+T_1 s} + \frac{T_2}{1+T_2 s} \tag{2.121}$$

$$U_2 = \frac{T_1^{\,2}}{(1+T_1 s)^2} + \frac{T_2^{\,2}}{(1+T_2 s)^2} \tag{2.122}$$

The C-curve is given by:

$$C_t = \frac{\exp(-t/T_1) - \exp(-t/T_2)}{T_1 - T_2} \tag{2.123}$$

For parameter finding, equations 121 and 122 give:

$$\left(\frac{2}{U_1^{\,2} - U_2} - s^2 \right) = \frac{T_1+T_2}{T_1 T_2} s + \frac{1}{T_1\ T_2} \tag{2.124}$$

which can be plotted as a straight line. If a plug flow element T_p is present, U_1 must be replaced by $(U_1 - T_p)$, and T_p can be adjusted

to give the best straight line in the usual manner.

IV CONCLUSION

It can be seen that, although Transfer-function methods are not applicable to all possible models, they can incorporate up to four parameters. The models developed in this chapter were considered because they appeared relevant to the present equipment; no doubt other models can be investigated on this line.

For models that are not amenable to the graphical methods just described, the transfer- and U-functions can still be a useful way to minimise tailing problems[M12, M13].

The use of transfer-function methods will be illustrated in the next two chapters.

NOTATION FOR CHAPTER 2

A amplitude ratio, [-]

b recycle ratio in backflow cell model, [-]

c concentration in arbitrary units

C impulse response in terms of reduced time θ, [-]

C_t impulse response in terms of time t, $[s^{-1}]$

$\mathfrak{D}$ axial dispersion coefficient, $[m^2/s]$

E exit age distribution in terms of reduced time θ, [-]

E_t exit age distribution in terms of time t, [s^{-1}]

f_j fraction of total flow going to the j-th branch in a parallel arrangement, [-]

F step response in terms of θ, [-]

F_t step response in terms of t, [-]

$\mathfrak{F}$ normalised transfer function, [-]

$\mathfrak{F}^*$ unnormalised transfer function, in arbitrary units.

$H(t)$ unit step function, [-]

i $\sqrt{-1}$

I internal age distribution in terms of θ, [-]

I_t internal age distribution in terms of t, [-]

k parameter in diminishing backmix model, [-]

K proportionality constant of transfer function in arbitrary units.

L length of vessel, [m]

M_n n-th moment of C-curve, [-]

M_{tn} n-th moment of C_t-curve, [s^n]

M'_n n-th moment of C-curve about origin, [-]

M'_{tn} n-th moment of C_t-curve about origin, [s^n]

$\mathcal{M}_n(s)$ n-th moment of the weighted concentration curve about the origin (equation 2.70b), [s^{n+1} X concentration unit]

(Notation for Chapter 2, cont.)

n number of tanks in multi-tank models, [-]

parameter in diminishing backmix model, [-]

s Laplace transform parameter, [s^{-1}]

S slope of a straight line, [variable units]

t time, [s]

$\bar{t}$ first moment of the C_t-curve, [s]

$\bar{t}_o$ first moment of the outlet concentration curve, [s]

$\bar{t}_i$ first moment of the inlet concentration curve, [s]

T holding time of a flow component, [s]

T_t holding time of a stirred tank, [s]

T_p holding time of a plug-flow component [s]

T_o parameter in dimishing backmix model, [s]

u fluid velocity, [m/s]

U_o function defined by eqn.65, [-]

U_i function defined by eqn.66, [s]

U_2 function defined by eqn.67, [s^2]

v volumetric flow through system, [m^3/s]

V vessel volume, [m^3]

x axial distance, [m]

X fraction of reactant unconverted, [-]

X_b fraction unconverted in a batch reactor at time t, [-]

Y intercept of a straight line on the ordinate axis.

(Notation for Chapter 2, cont.)

α,β probabilities associated with flow states A,B respectively in stochastic models, [-]

$\delta(t)$ unit impulse function, [-]

ξ dimensionless distance, x/L, [-]

ψ phase angle in radian, [-]

π 3.14159 ...

σ^2 second moment of C-curve about $\bar{\theta}$, [-]

σ_t^2 second moment of C_t-curve about $\bar{t}$, [s^2]

θ reduced time, t/τ, [-]

$\bar{\theta}$ first moment of C-curve, [-]

τ holding time or space time, V/v or L/u, [s]

ω angular frequency, [radian/s]

Dimensionless numbers

Pe Peclet number, $uL/\mathfrak{D}$

Superscript

' differentiation

- Laplace transform

Subscript

A any substance

A,B states of a stochastic process

i inlet of vessel

j j-th vessel (in series flow)
j-th branch (in parallel flow)

o outlet of vessel

CHAPTER 3

AIR RESIDENCE TIME DISTRIBUTION AND AIR-FLOW PATTERN

I. INTRODUCTION

The performance of a spray dryer is strongly dependent on the flow and mixing patterns of both phases. Previously most information on the air-flow pattern has been obtained from either visual tests or velocity measurements. Residence-time distribution (R.T.D.) tests are attractive alternative studies because of their simplicity and easy practicability in industrial situations. R.T.D. data also lend themselves readily to the quantification of mixing phenomena and of the non-ideality of flow patterns.

Previous works on the R.T.D. of the air in spray dryers are few: one can quote Paris et al.[P2], Place et al.[P9] and some unpublished research of industrial workers[B9]. In the present work, an attempt will be made to model both the drying air stream and the atomising air jet in the existing dryer, using a random pulse injection combined with Laplace transform and other data processing techniques described in the last chapter. The changes in the behaviour of the column with changes in drying air and atomising air rates will be studied. R.T.D. modeling will be checked with velocity measurements and results from smoke tests. From the data obtained it is hoped that some general remarks on the design and operation of spray dryers can be made.

II. THEORETICAL BACKGROUND

The theoretical background of R.T.D. modeling in general has been described in the last chapter. Before describing the experiment and its results, however, some speculations will be made on what can be expected concerning the air-flow pattern.

II.1 Drying air-flow pattern

If entrance effects can be neglected in the drying chamber, axially dispersed plug-flow (A.D.P.F.) will take place at least in part of the dryer. Taylor[T 3] derived theoretical expressions for the axial dispersion in infinite pipes. His results can be written as:

(a) Streamline flow: $Pe_D = 192\ Sc\ Re\ ,\quad Re < 2400$ (3.1)

(b) Turbulent flow: $Pe_D \simeq \log_{10} Re - .87\ ,\quad 2400 < Re < 10^6$ (3.2)

where Re is the Reynolds number based on the pipe diameter, Pe_D the Peclet number also based on the pipe diameter, and Sc the Schmidt number of the fluid. In practice equation 1 has been verified, but equation 2 tends to give high Peclet numbers compared to experimental results[L6], although the trend (Pe_D increasing with measured Reynolds number) is correct.

Taylor's results, being based on infinite pipes, are not directly applicable to the present equipment, but can serve as a basis for comparison. When the vessel length is finite, entrance and exit effects will modify the flow and turbulence profiles. The use of a closed-ended ADPF model does not improve the situation because of the magnitude of the turbulence changes, and an open-ended ADPF model will serve just as well.

A more realistic model should take into account the change in the turbulence pattern along the vessel. The change may be sudden, as in the tanks-in-series-and-plug-flow (TSPF) model or the second-order and plug flow model, or it may be gradual, in which case the diminishing-backmix model with or without plug flow would be a better approximation (see chapter 2, figure 4c). On the other hand, the backflow-cell model is also a good candidate for describing the large structure of turbulence.

Some insight into the hydrodynamic situation can be obtained by considering the drying chamber, with its sudden expansion at the inlet end, as a jet-stirred vessel, which has been studied before.(S9,W7,W8)

In fairly squat vessels (length to diameter ratio $\leqslant 3$) with a small central orifice at each end through which fluid is injected and withdrawn, the model in figure 1b has been found to apply. Sinclair and McNaughton(S9) gave the following expressions for its parameters:

$$T_t/\tau = 1 \tag{3.3}$$

$$p = \frac{2r_o}{k_e L} \tag{3.4}$$

$$\frac{T_p}{\tau} = \frac{k_e L r_o}{D^2} \tag{3.5}$$

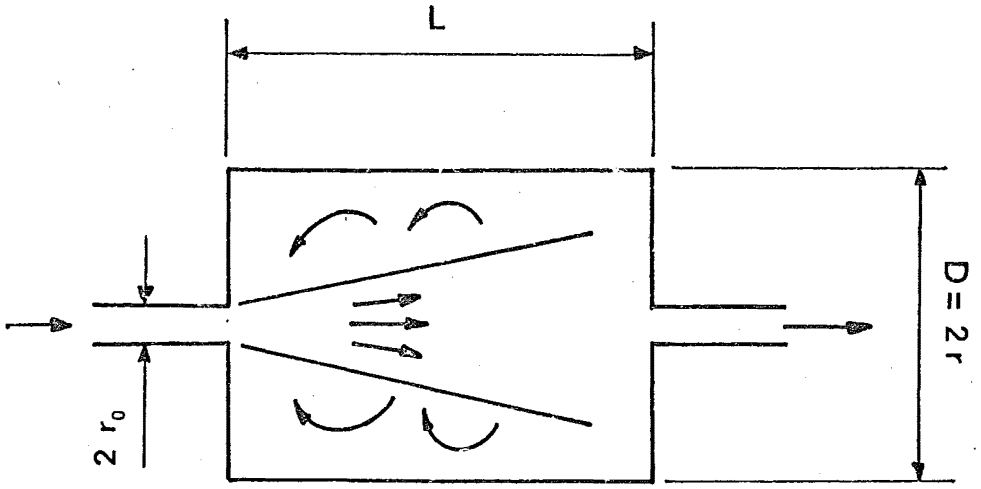
where τ is the holding time and k_e is a constant characterising the rate of entrainment of air into the jet, and k_e has the value of 0.23 for air (Chapter 6, eqn.31).

If this model applies to the spray dryer as a whole ($L = 2200$ mm, $D = 400$ mm, $r_o = 25.4$ mm), then from those equations:

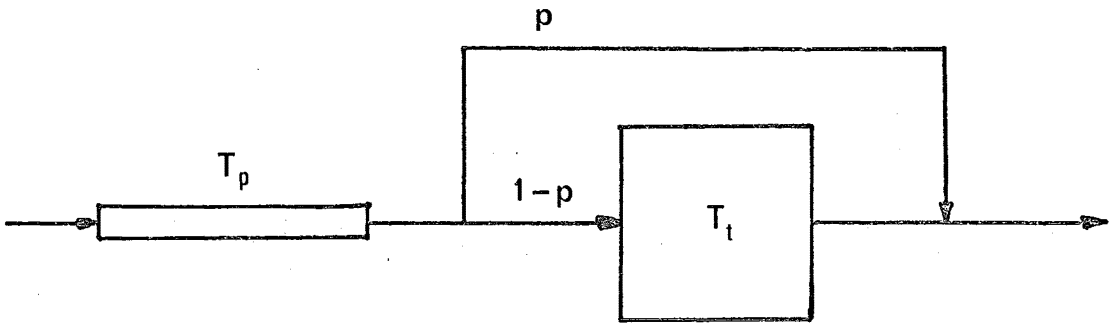
$$p = .1$$

$$T_p/\tau = .08$$

i.e. the whole chamber behaves almost as a single stirred tank. On the other hand the flow may also settle down to a plug flow pattern before the end of the vessel is reached, in which case T_p will increase. Furthermore the single-tank approximation would not strictly hold for the high r_o/r ratio (1/8) that is the case on this equipment.



(a) Jet-stirred vessel



(b) Model

FIGURE 3.1: JET-STIRRED VESSEL & MODEL

II.2 Interaction between the atomising air flow and the drying air stream

Consider first a small jet (representing the atomising air) injected into an external parallel cocurrent stream of air (figure 2). The flow of such a system is governed by the Craya-Curtet number:(B7,C9,M15)

$$Ct = \left[\frac{r_o^2 (u_o^2 - u^2) + u^2 r^2/2}{v_t^2 / (\pi r)^2} - \frac{1}{2} \right]^{-\frac{1}{2}} \qquad (3.6)$$

It has been found experimentally that if $Ct < .75$, recirculation will take place (figure 2c). For the spray drying chamber and nozzle being considered,

$$u/u_o \approx 10^{-3} \qquad (3.7)$$

$$r_o/r \approx 10^{-3} \qquad (3.8)$$

$$v_t \simeq \pi r^2 u \qquad (3.9)$$

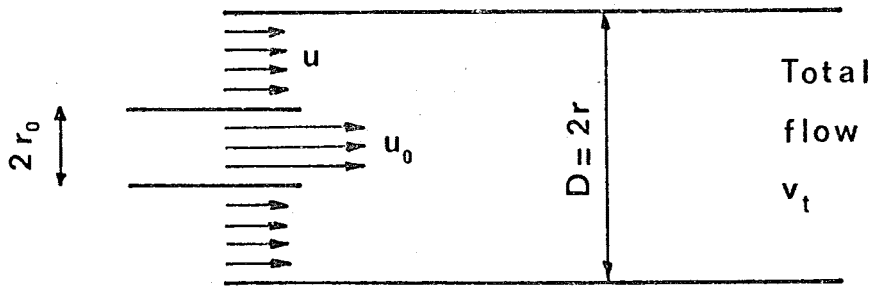
hence

$$Ct \simeq \frac{ru}{r_o u_o} \qquad (3.10)$$

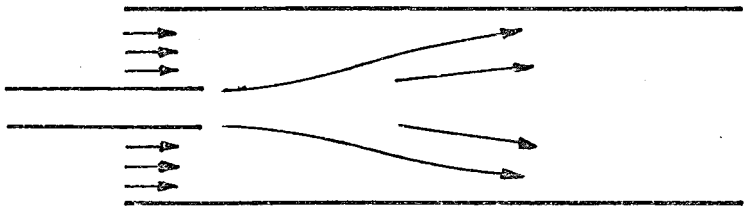
(the square root of a momentum ratio)

Hence in the present case Ct is proportional to the flow ratio of the drying air to the atomising air. As can be seen from equations 7, 8 and 10, Ct is of order one and recirculation due to the nozzle may or may not occur.

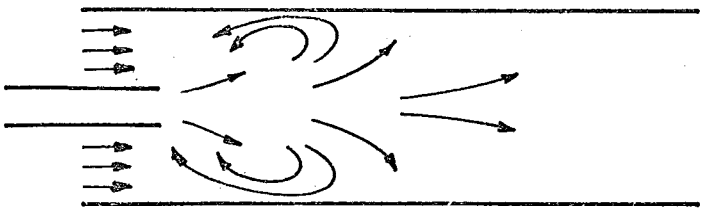
In the actual situation, the external (drying air) flow will not be parallel because of entrance effects. However the previous results may be generalised by saying that the jet effect will become dominant and have an important influence on the drying air flow for small Craya-Curtet numbers (large atomising air rate to drying air rate ratios).



(a)



(b) No recirculation



(c) Recirculation

FIGURE 3.2 : JET IN COCURRENT DUCTED FLOW

II.3 Expected atomising air R.T.D.

Will the mean residence time of the jet of atomising air be greatly different from that of the drying air ? To predict this, one has to explore the dynamics of jet motion. This subject will be considered in more detail in Chapter 6. For the moment, the following results will be assumed for an air jet into which a tracer of concentration c is injected [A3] (Figure 3) :

$$c = c_m\left[1 - \left(\frac{y}{r_j}\right)^{1.5}\right], \quad y < r_j \qquad (3.11)$$

$$= 0, \quad y > r_j$$

$$c_m = \frac{9\, r_o c_o}{x - 8r_o} \simeq \frac{9\, r_o c_o}{x} \qquad (3.12)$$

$$r_j = 0.22\,(x - 8r_o) \simeq 0.22\, x \qquad (3.13)$$

where c_m is the axis value of the tracer concentration at x metres from the orifice and c_o its value at the orifice.

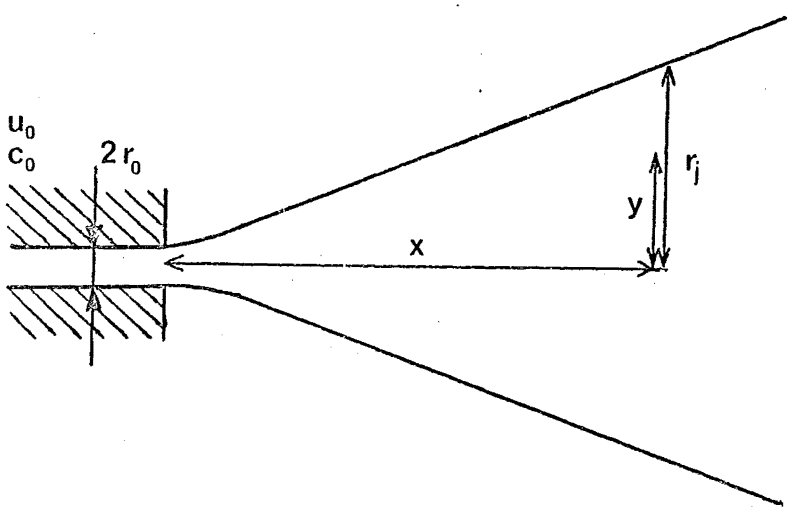


FIGURE 3.3 : SUBMERGED JET

The total amount of tracer in the jet from x = 0 to x is:

$$m = \int_{x=0}^{x} \int_{y=0}^{r_j} c(2\pi y)\,dy\,dx$$

which, on substituting in equations 11, 12 and 13, gives

$$m = 0.093\ \pi r_o c_o x^2 \quad . \tag{3.14}$$

The rate of tracer injection is

$$\dot{m} = \pi\ r_o^2\ u_o c_o \quad . \tag{3.15}$$

Hence the mean residence time in the jet for the tracer is

$$\tau_{jo} = m/\dot{m} = \frac{0.093\ x^2}{u_o r_o} \quad . \tag{3.16}$$

The mean velocity of the tracer in the jet is

$$u_j = dx/d\tau_{jo} = \frac{u_o r_o}{0.186\ x} \quad . \tag{3.17}$$

If the jet is injected into a stream with velocity u_∞, the two velocities can be superimposed. Hence the mean residence time of the tracer between x = 0 and x = L is:

$$\tau_j = \int_o^L \frac{dx}{u+u_j}$$

$$= \frac{L}{u} - \frac{u_o r_o}{0.186\ u^2}\ \ell n\left(1 + \frac{0.186\ uL}{u_o r_o}\right) \tag{3.18}$$

Without the jet, the mean residence time of a tracer in the stream would be $L/u = \tau$. Hence the ratio between the mean residence time of the jet and that of the main stream is:

$$\frac{\tau_j}{\tau} = 1 = \frac{\ell n(1+\beta)}{\beta} \tag{3.19}$$

where

$$\beta = \frac{0.186\ Lu}{u_o r_o} \quad . \tag{3.19b}$$

In the present equipment,

$L = 2200$ mm

$r_o = 0.9$ mm

$u_o \simeq 350$ m/s

$u \simeq 0.1$ m/s to 2 m/s

hence

$\beta = 0.13$ to 2.6

$\tau_j/\tau = 0.06$ to 0.74 .

So if the external flow is non-turbulent and parallel, the jet mean residence time can be appreciably lower than the external flow residence time, especially as the external velocity decreases. Whether this is the case or not in a real situation depends on how the turbulence in the external (drying) air affects the jet: if the jet is broken up early, then the two R.T.D. will become closer.

III. EXPERIMENTAL DETAILS

III.1 Tracer kinetics apparatus

(a) Pulse injection: The tracer used is Freon-12 (dichloro-difluoro-methane, CCl_2F_2) which is supplied in liquified form in cans under a vapour pressure of 550 kPa at 20°C. For the drying air, injection is done through a solenoid valve modified to give a narrow pulse (figure 4a). When the valve opens, the pressure on its downstream side increases and a "puff" of Freon is injected into the stream. However, the reverse flow from the air stream to the vacuum is quickly re-established, thus ensuring that the Freon pulse is of short duration. The injection pattern has been found to be highly reproducible, as

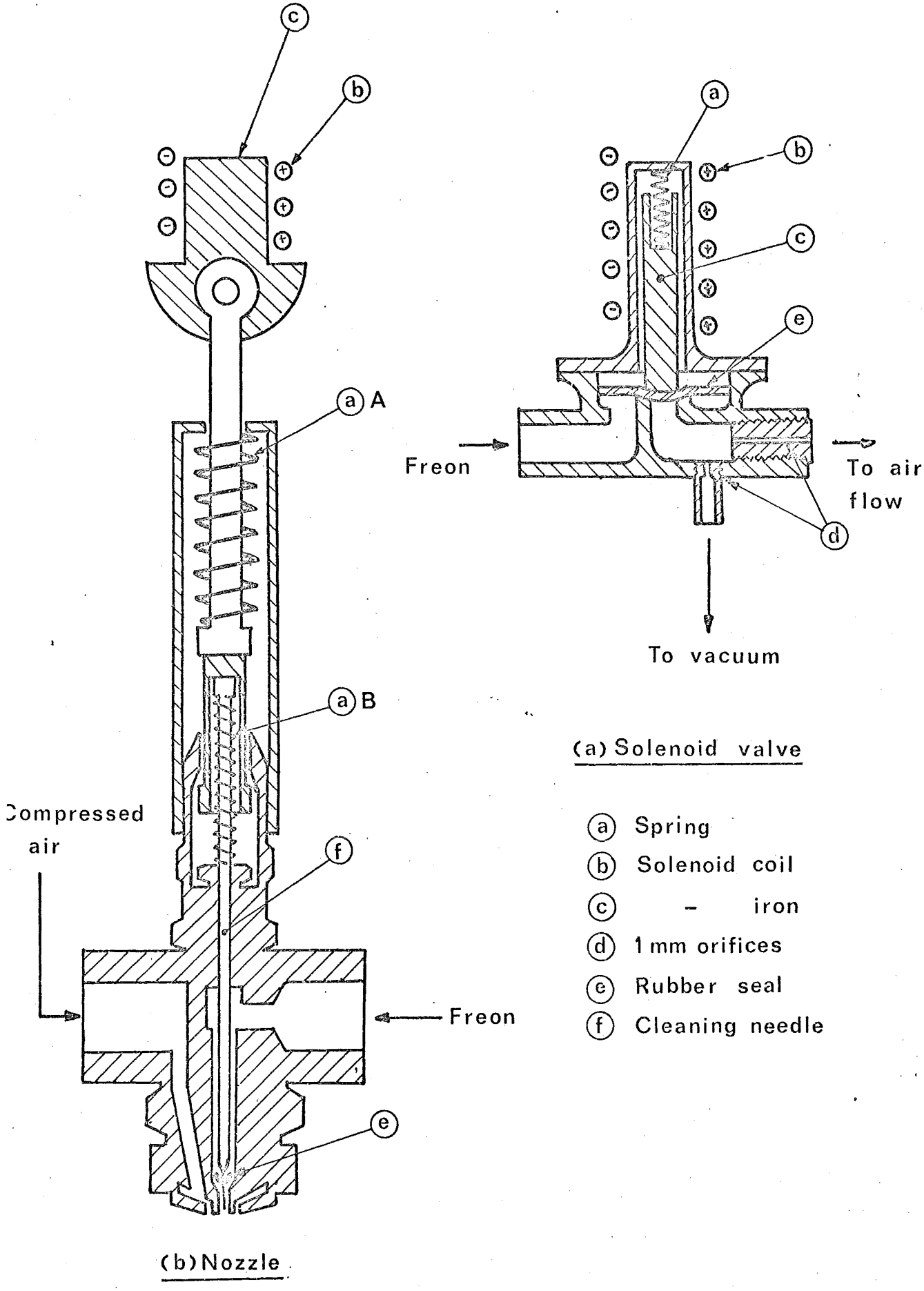


FIGURE 3.4: FREON INJECTION

evidenced by concentration measurements a short distance from the injection point.

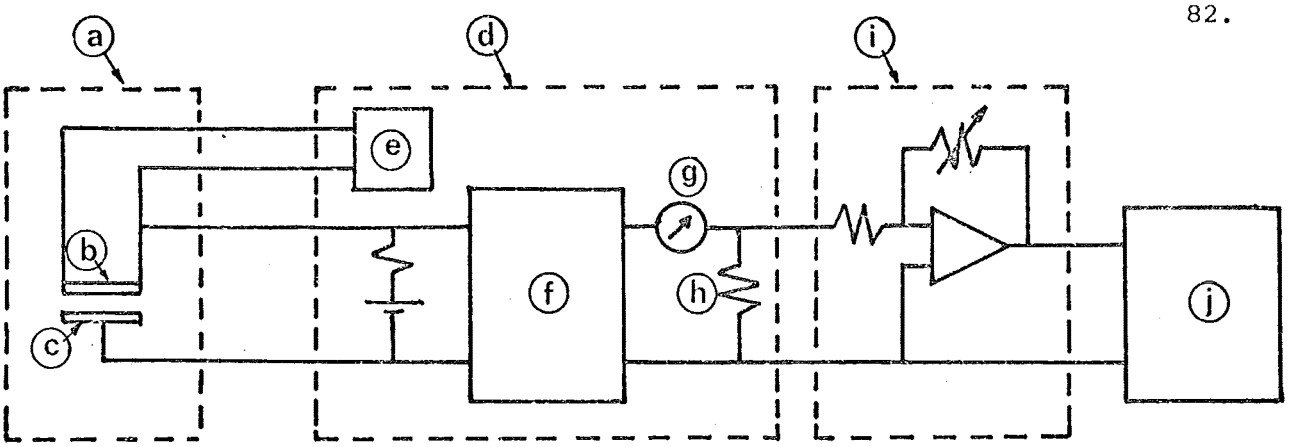
The injection system for the atomising air is shown in figure 4b. The liquid inlet is connected to the Freon and the liquid orifice is normally closed by the cleaning needle with a rubber gasket, the needle being held down by a strong spring A. When the solenoid is activated, it counteracts this spring, and a weak spring B pushes up the needle to let through a pulse of Freon.

The solenoids are activated by a unit pulse generator (manufacturer: General Radio; type: 1217-B) operating through a relay. This relay also sends a pulse to the recorder to mark the injection time (figure 6). The pulse duration can be varied from 1 μs to 1 s, but in practice pulses of 10 to 60 milliseconds were used.

(b) Pulse detection: a Dynavac leak detector (manufacturer: Dynavac High Vacuum Ltd (Australia); type HLD1) is used to monitor the Freon concentration in the air. An air stream is withdrawn from the flow and passes over the probe, which consists of a red-hot platinum anode and a cathode (figure 5). Small amounts of halogen vapour in the air will markedly increase the positive ion emission of the platinum wire, causing a current to flow. The signal is then amplified and fed to a recorder.

The recorder used is a six-channel galvanometric fast-response recorder (manufacturer: Honeywell; type: Visicorder model 1406), which uses beams of ultraviolet light to write on photosensitive paper. It has a maximum chart speed of 635 mm/s (25 in/s) and the frequency response amplitude ratio remains flat to $< \pm 10\%$ up to 200 Hz.

The air flow past the probe is kept constant at about 70 cm^3/s.



Circuit diagram

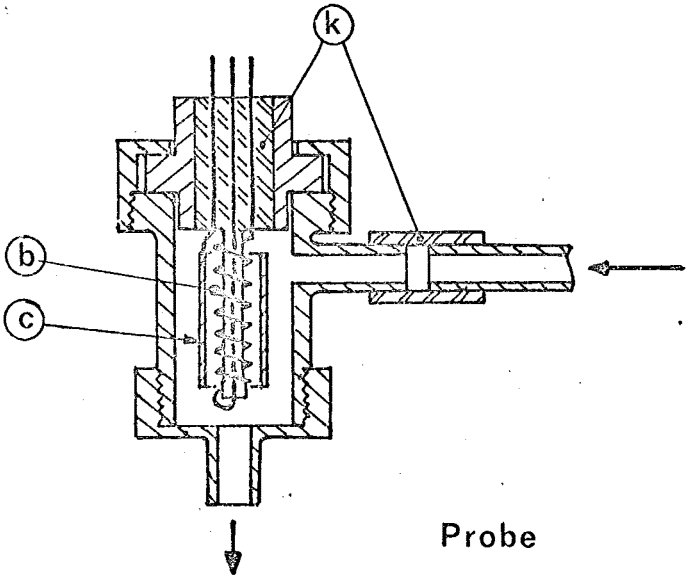


FIGURE 3.5: FREON DETECTION

a Probe
b Pt anode
c Cathode
d Control box
e Heating supply
f Cathode follower
g Galvanometer
h 500Ω resistor
i Operational amplifier
j Recorder
k Insulator

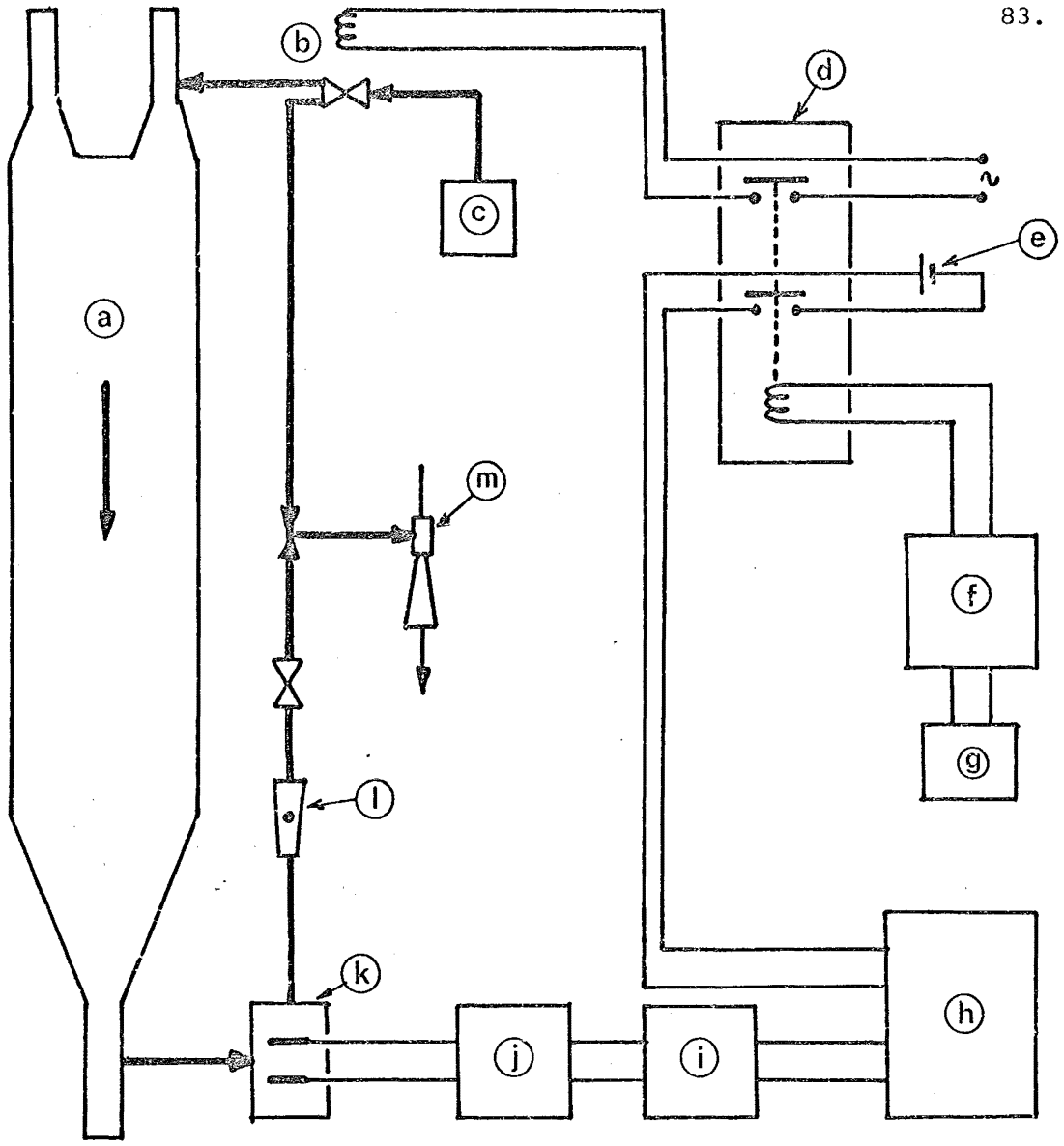


FIGURE 3.6: BLOCK DIAGRAM, AIR RTD EQUIPMENT

a	Dryer
b	Solenoid valve, n.c.
c	Freon
d	Relay box
e	1.5V cell
f	Unit pulse generator
g	Trigger
h	Multichannel recorder
i	Operational amplifier
j	Dynavac control box
k	Probe
l	Rotameter
m	Water ejector

The total volume of the tubing between the sampling point and the probe, plus that of the probe housing, is estimated to be 12 cm^3. Thus the detection system has a time constant of about 12/70 = 0.17 s, which is small compared to that of the column (1 to 30 s).

Since the total transfer function of the system between the injection point and the recorder is the product of the transfer function of the drying chamber and that of the detecting system (the latter including the probe housing and all the electronic equipment up to the recorder), the response curve of this detecting system is mathematically equivalent to the "inlet concentration curve" as defined in Chapter 2. It can be measured simply by sampling the air a short distance (5 cm) below the Freon injection point. This was done and the curve obtained was highly reproducible, being independent of the column operating conditions.

III.2 Velocity and turbulence measurement

A DISA constant-temperature hot-wire anemometer (figure 7) was used to measure the velocity and turbulent profiles in the column. The probes (type DISA 55A22) are made of 5 μm diameter x 1.2 mm platinum-coated tungsten wire having a resistance of 3.6 ± .6 ohms at 20^oC.

(a) Mean velocity measurement: Detailed descriptions of the theory of hot-wire anemometry can be found elsewhere[H13]. In the present work the following equation, based on King's law or Kramer's law, will be used:

$$V^2 - V_o^2 = B\sqrt{\bar{u}} \qquad (3.20)$$

where V is the d.c. voltsge across the bridge containing the probe, V_o its value in quiescent fluid, $\bar{u}$ the mean fluid velocity and B is a constant depending on the wire, the fluid and the overheating ratio α:

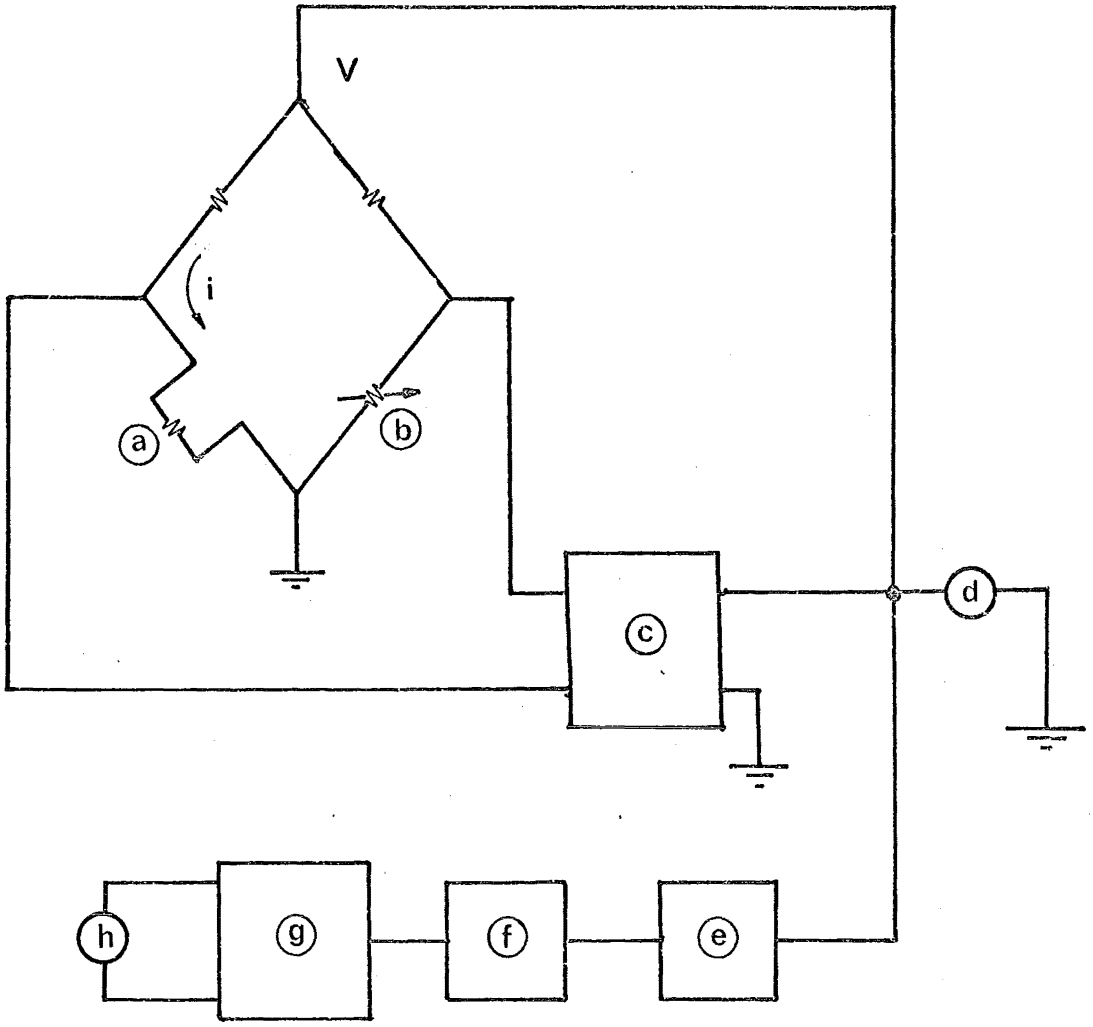


FIGURE 3.7: BLOCK DIAGRAM, HOT-WIRE ANEMOMETER

a Hot-wire probe
b Decade resistors
c Amplifier with transconductance g_{tr}
d D.c. voltmeter
e High-pass filter
f Low-pass filter
g A.c. amplifier
h A.c. voltmeter

$$\alpha \equiv (R - R_c) / R_c \qquad (3.21)$$

R is the hot wire resistance and R_c the cold wire resistance, i.e. measured at the fluid temperature.

Several probes were used as they break now and then. For each B was determined by calibrating the probe in a wind tunnel against a pitot tube. A typical value is $B = 9.6\ V^2/m^{\frac{1}{2}}s^{-\frac{1}{2}}$.

Because of eddies in the air stream, the velocity fluctuates and the d.c. voltage V cannot be read directly. Instead V was integrated over an interval of 30 to 120 seconds by means of an electronic integrator.

(b) Turbulence measurement: The relative turbulence intensity, $u'/\bar{u}$, where u' is the root-mean-square turbulent velocity component perpendicular to the wire, can be found by[D6]:

$$\frac{u'}{\bar{u}} = \frac{4VV'}{V^2-V_o^2}$$

where V' is the rms value of the fluctuations in V.

The instrument has a high-pass filter (5 to 10^3 Hz) and a low-pass filter (10^3 to 10^5 Hz) which can be used to give a stepwise spectrum of turbulence. When doing this, the frequency response of the system must be taken into account. A Bode diagram is given by the manufacturer [D6] for a particular wire at a few sets of operating conditions. To extrapolate to other situations the following equation[H13] can be used:

$$\tau_\omega \propto \frac{\alpha}{R_o i^2 (1+2\alpha R g_{tr})} \qquad (3.22)$$

where τ_ω is the time constant of the anemometer, R_o is the resistance of the probe at a certain reference temperature, i the d.c. current through the wire and g_{tr} the a.c. transconductance of the amplifiers

in the instrument. On the present instrument $g_{tr} \simeq 8$ mho's, $R \simeq 5$ ohms, so that equation (22) simplifies to

$$\tau_\omega \propto \frac{1}{R_o i^2 R\, g_{tr}} \propto \frac{1}{R_o i^2 R} \tag{3.23}$$

Also on this instrument

$$i = \frac{V}{R+100\Omega} = \frac{\sqrt{V_o^2 + B\sqrt{u}}}{R+100\ \Omega} \tag{3.24}$$

where 100 Ω is the resistance in series with the hot wire in the bridge circuit of the anemometer (figure 7). Hence,

$$\tau_\omega \propto \frac{(100\Omega + R)^2}{R_o R(V_o^2 + B\sqrt{u})} \tag{3.25}$$

IV. EXPERIMENTS CARRIED OUT

R.T.D. measurements were carried out at 28 drying air-flow rates, but only on 6 of these were the R.T.D. of the atomising gas investigated. The drying air velocity in the chamber varied from 0.055 m/s to 2.2 m/s, the drying air flow rate from 6.9×10^{-3} m^3/s to 0.276 m^3/s (as calculated from the residence-time data). The drying air was not heated, but due to compression its temperature may go up to 38^oC at the higher flow rates.

Nozzle no.2 (Chapter 1, Table 1) was used in all runs except run 1, where nozzle no.1 was used. The atomising air pressure varied from 0 to 380 kPa gauge, and its discharge rate from 0 to 1.65×10^{-3} kg/s or 1.27×10^{-3} m^3/s at standard conditions (graphs of atomising air rates can be found in Appendix B.II). No liquid feed was atomised in any run. Since the momentum of the liquid is

negligible when compared with that of the atomising gas (in ordinary operation the two flows are of similar magnitude but the liquid velocity is at most 4 m/s as compared with nearly sonic velocity for the air), it can be assumed that the presence of a liquid flow would not significantly affect the results of the present experiments.

On four runs (runs 5, 9, 14 and 17 in Table 1) velocity and turbulence profiles were measured at the top, middle and bottom of the vessel. The influence of the atomising air jet on the velocity profile and the turbulence spectrum was also investigated (run 17).

A summary of the experiments carried out is shown in Table 1. Henceforth the runs will be referred to by their number in this table and an index denoting the nozzle pressure. For example, run 20b is that done at a drying air velocity of 1.22 m/s and a nozzle pressure of 70 kPa above atmospheric pressure.

TABLE 3.1

Operating conditions in air R.T.D. experiments

Run	Air vel./ms^{-1}	Whether atomising R.T.D. measured	Atomising pressures used / kPa				
			a	b	c	d	e
1	.055	Y	0	140	205	275	380
2	.055	Y	0	70	180	275	380
3	.077		0	-			
4	.127		0	-			
5	.135		0	69	138	207	345
6	.144	Y	0	69	180	275	380
7	.183		0	-			
8	.23		0	-			
9	.24		0	69	138	207	345
10	.29	Y	0	69	180	275	380
11	.31		0	-			
12	.41		0	-			
13	.45		0	-			
14	.54		0	69	138	207	345
15	.57		0	-			
16	.61	Y	0	69	180	275	380
17	.69		0	69	138	207	345
18	.73		0	-			
19	.95		0	-			
20	1.22	Y	0	69	180	275	380
21	1.27		0	69	138	207	345
22	1.32		0	-			
23	1.57		0	-			
24	1.59		0	-			
25	1.80		0	-			
26	2.16		0	-			
27	2.2		0	-			
28	2.2		0	-			

N.B. Nozzle 2 used in all runs except run 1.

Y = yes.

V. RESULTS AND DISCUSSIONS

V.1 Results of R.T.D. measurements

A summary of all the results can be found in Appendix A. All runs were repeated at least once and the average results ($\bar{t}$, σ^2, Pe and other parameters) tabulated. In the following section only typical samples will be described and discussed. As there is no qualitative difference between the drying air R.T.D. and the atomising air R.T.D., only the former will be discussed until section V.1.7.

V.1.1 Response curves

Some response curves for a medium air flow rate with various atomising pressures are given in Figure 8. There appears to be no qualitative difference between runs done at different drying air rates. At low air rates the base line (c = 0) may shift during a run, by as much as 1.5% of the peak value. An exponential decay curve was fitted to the tail of each curve above 3 times the first moment.

Visual examination of the curves show the following points:

(1) There is a noticeable plug flow section where c = 0.

(2) There is as expected a significant effect of the atomising air rate on the drying air R.T.D. This effect will be studied in detail later.

(3) On some of the runs a bypass is observable, as shown by a sharp peak early in the response curve.

(4) There is either some recycling, or non-stationary behaviour, or both, as evidenced by the oscillations in the response. This effect is particularly noticeable at low air velocities (below 0.2 m/s in the column), which is not surprising since the flow always tends to be unstable at or near the transition point (at a velocity of 0.1 m/s, the Reynolds number of the column would be about 3000).

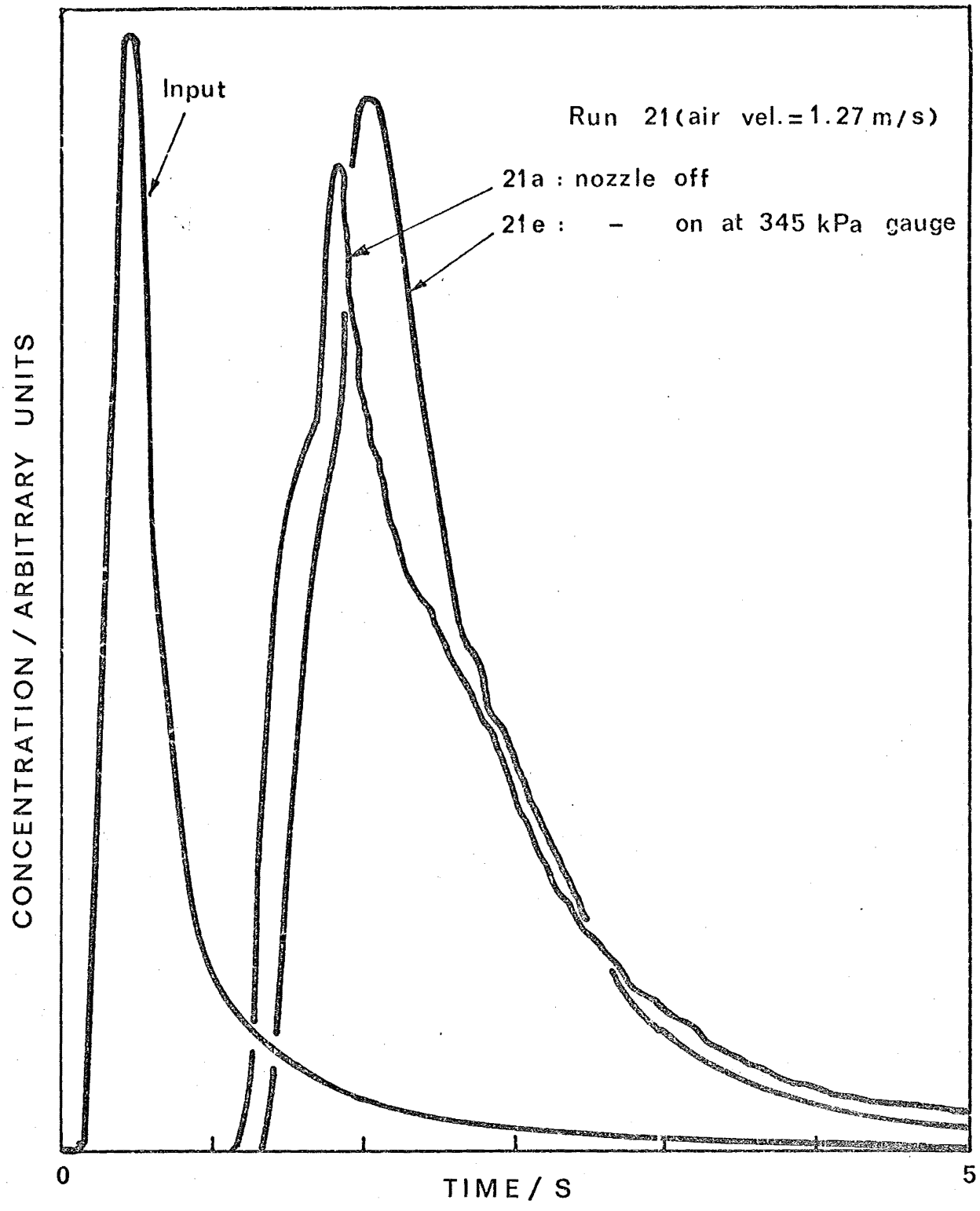


FIGURE 3.8: CONCENTRATION CURVES, DRYING AIR

V.1.2 Moment analysis

Due to the long tail of both the input and output concentration curves, and the uncertainty in the baseline, it is difficult to apply the method of moments rigorously. The iterative truncation method suggested by Jagota et al.[J1] was tried on run 24: the input curve is cut off at an arbitrary time t_1 ; the output curve is cut off at $t_2^{(1)}$, and the residence time $\bar{t}^{(1)}$ is calculated. Then the output curve is truncated at $t_2^{(2)} = t_1 + \bar{t}^{(1)}$ and a new mean residence time $\bar{t}^{(2)}$ is found, and so on until $\bar{t}^{(n)} = t_2^{(n)} - t_1$. The results are strongly dependent on t_1 :

For t_1 = 5s , $\bar{t}$ = 1.33 s

σ^2 = 0.132

For t_1 = 7s , $\bar{t}$ = 1.43 s

σ^2 = 0.249

This is not surprising since the truncation method described here cuts off the output concentration curve too early, where it still has a significant value. For the same reason this method invariably gives low values of $\bar{t}$ and σ^2 compared with any of the transfer function methods. The second moment is especially sensitive to changes in t_1 .

V.1.3 Transfer-function analysis

The models listed in figure 4 of Chapter 2 were tried on the response curves, using the transfer-function methods described in that chapter. Complete results are shown in Appendix A.

(a) The axially dispersed plug flow (A.D.P.F.) model:

U_1^{-2} was plotted against s according to equation 80 of chapter 2, as shown in figure 9. For a true A.D.P.F., the plot should be linear. It can be seen that this is not the case here. If, nevertheless, the

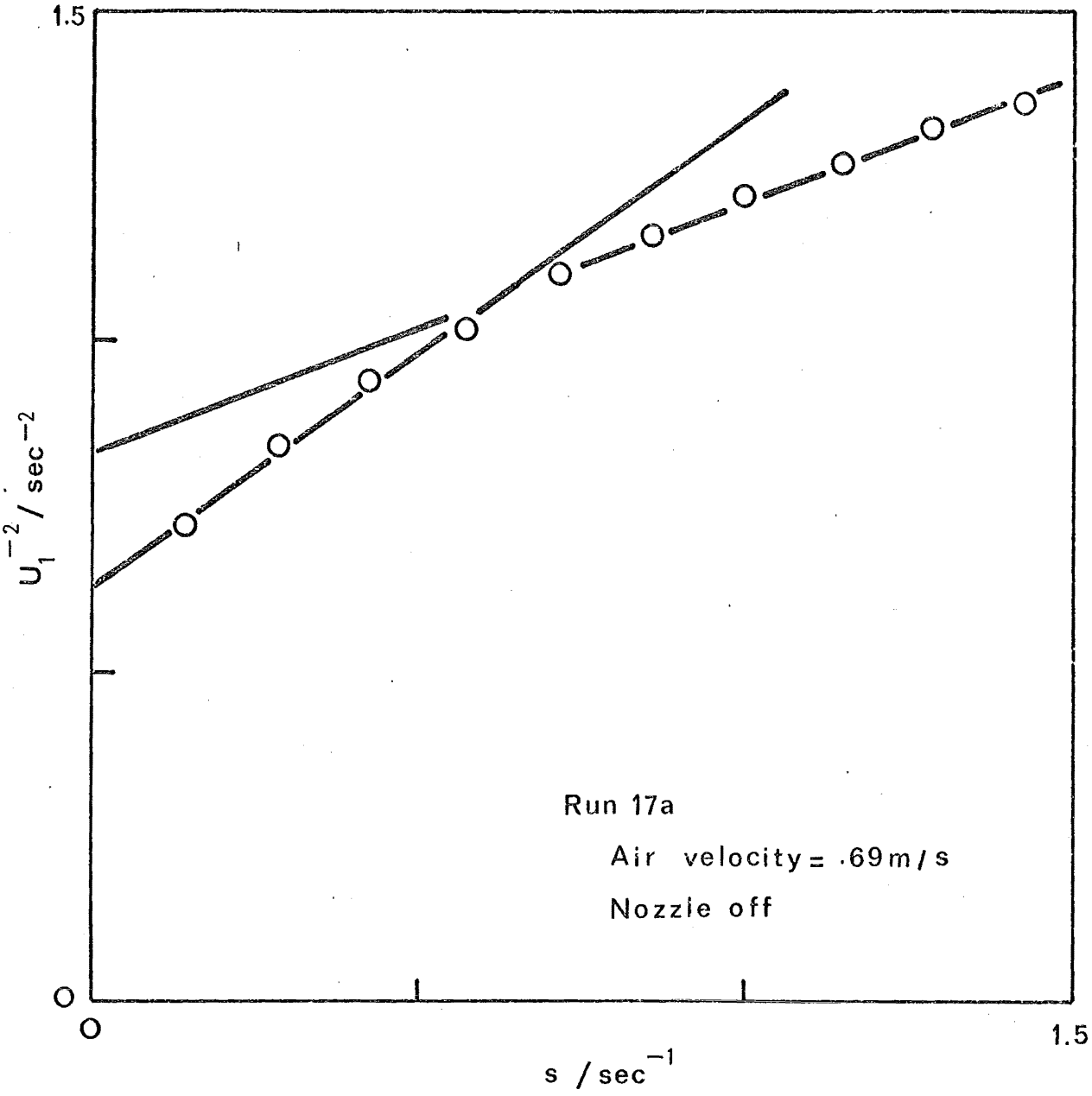


FIGURE 3.9: TRANSFER-FUNCTION ANALYSIS, DRYING AIR, ADPF MODEL

model is fitted to the data, a straight line can be drawn through the first 4 points ($s\tau \simeq .5$ to 2) or through the remaining points ($s\tau \simeq 2$-5) and the differences will give an estimate of the errors involved. Since τ is the inverse square root of the intercept, the error in τ is not too large (± 7% for the case shown) but the error in Pe is usually much higher (± 20 %). For the results shown in Appendix A, a range $s\tau$ = 0.5 - 2 were used following Michelson and Østergaard's recommendation[M13].

The curvature of the U_1^{-2} plots is always negative (concave down), i.e. U_1 decreases with increasing s more slowly than for true A.D.P.F. flow. This would indicate that there is a plug flow region T_p in the system (or at least a region with low dispersion coefficient), since $U_1(s) + T_p$ decreases relatively more slowly than $U_1(s)$ alone (see Chapter 2, section III.2.3).

Although the model is not strictly valid, it is the only two-parameter model attempted and can still be a useful characterisation of the average degree of backmix in the column.

(b) The second-order-and-plug-flow model (S.O.P.F.)

$\{2/[(U_1 - T_p)^2 - U_2] - s^2\}$ was plotted against s (Chapter 2, eqn.124) as shown in figure 10. The plug-flow time was measured directly from the response curve. The calculated values of the tank times are 4.54 s and 0.11 s , so that the vessel behaves almost as a single tank with plug-flow in series. However, the graph is not linear and errors in the slope and the intercept are very large (the intercept may be as low as 0, in which case the tank times would be infinite). It was concluded that this model is not useful to the present arrangement.

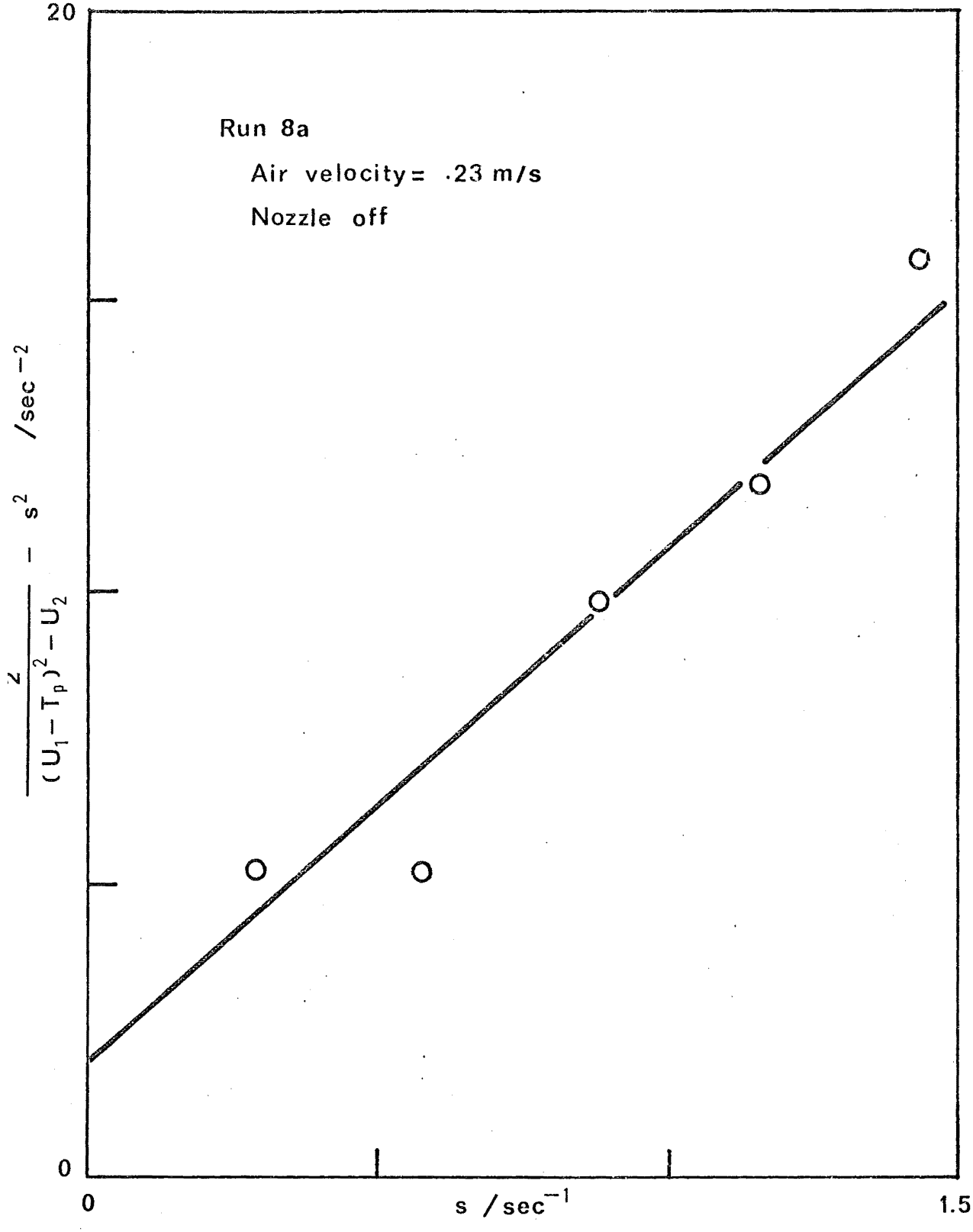


FIGURE 3.10 : TRANSFER-FUNCTION ANALYSIS, DRYING AIR, SOPF MODEL

(c) The tanks-in-series-and-plug-flow (T.S.P.F.) model:

Typical plots of $U_2^{-\frac{1}{2}}$ and $U_1/\sqrt{U_2}$ against s (Chapter 2, equations 87,88) are shown in figure 11. These plots are not straight below s = 2, but are quite linear above this value. In the time domain this means that the model would predict accurately the response curve at small or negative $t-T_p$ but would be wrong in the tail region.

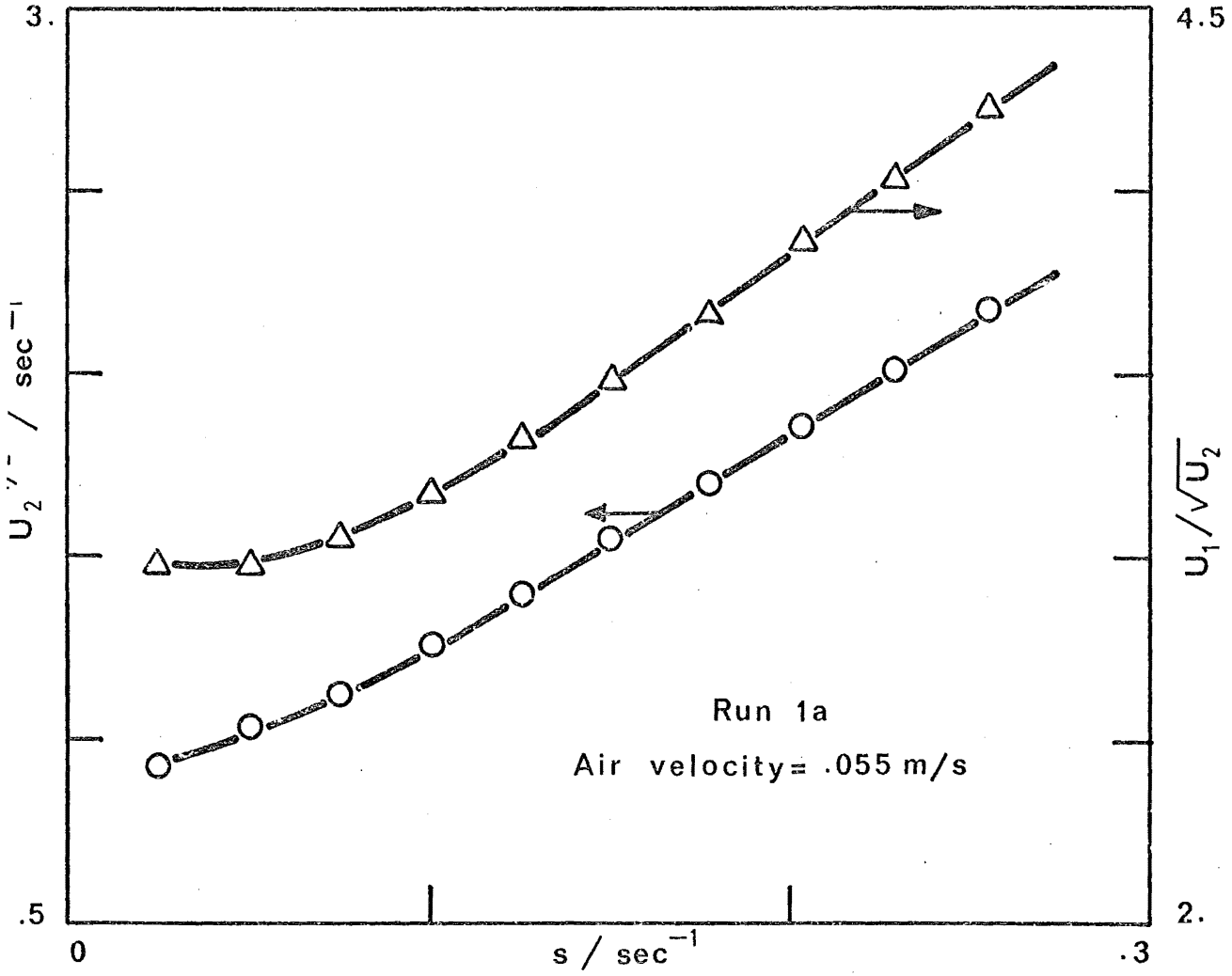
At low air rates almost all plots have a positive curvature (concave up) at low s, i.e. as s decreases, U_2 increases more slowly than expected for a TSPF model, which would be the case if the tail is smaller than expected. The trend is reversed at high drying air rates. The latter case is probably due to the presence of a deadwater region (a steady eddy) which exchanges tracer slowly with the rest of the vessel. This would not be surprising since at high velocities the jets from the inlets would be more pronounced and able to form a steady eddy near the top of the column. At low velocities, because of the unsteadiness of the flow, no durable eddy can be formed.

It was stated in Chapter 2 that one of the parameters, for example the plug flow time T_p, can be calculated in two ways (Chapter 2, equations 91 and 92), thus giving a check on the validity of the model. This was done on all runs and typical results are shown in Table 2. It can be seen that the two equations are in agreement to within 0.8%. For all other runs the discrepancies are below 2%.

TABLE 3.2

Plug-flow time of T.S.P.F. model, calculated by two methods

Run	T_p/s (eqn.2.91)	T_p/s (eqn. 2.92)
10a	3.41	3.40
10b	3.30	3.29
10c	2.94	2.92
10d	2.44	2.44
10e	2.40	2.38



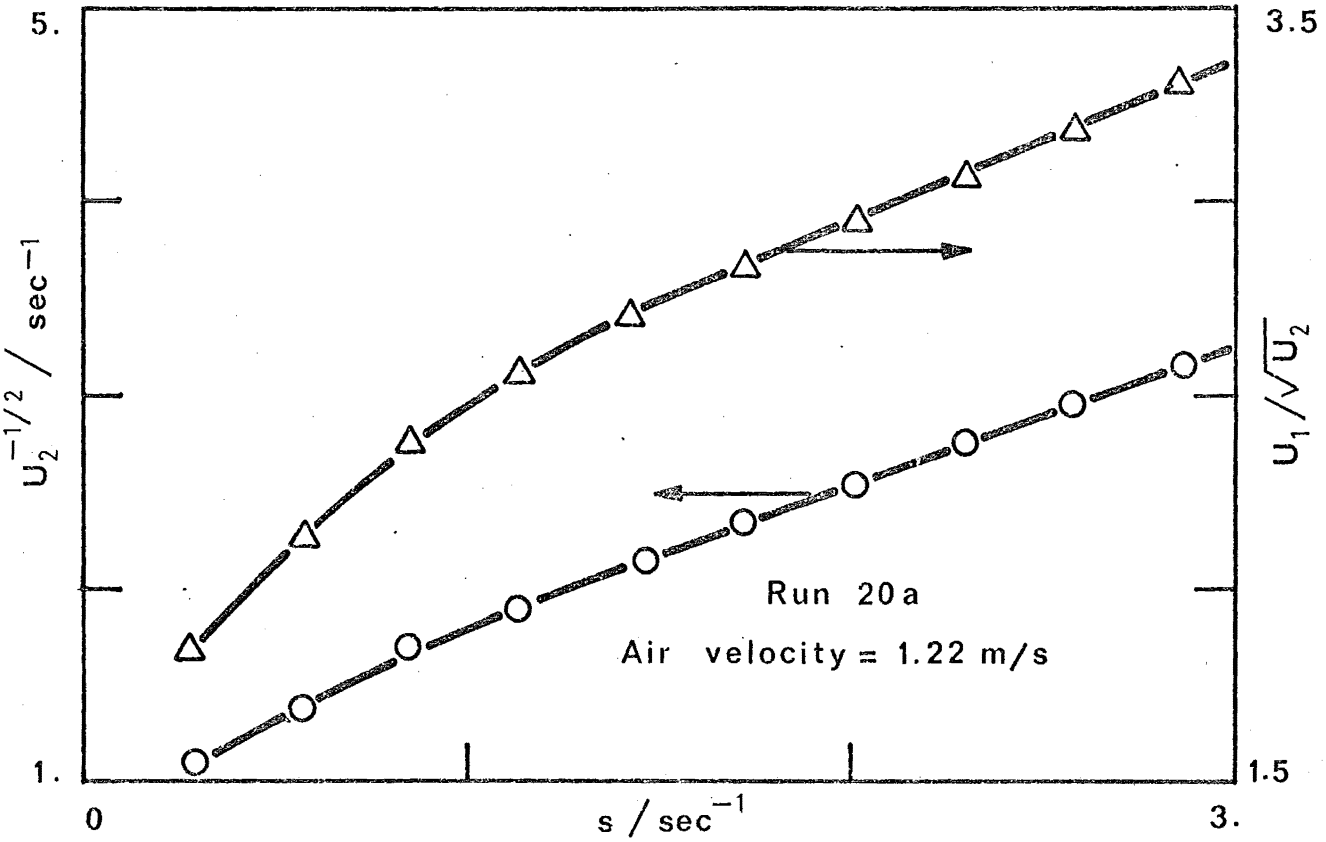


FIGURE 3.11: TRANSFER-FUNCTION ANALYSIS, DRYING AIR, TSPF MODEL

The calculated values of T_p are plotted in figure 12 against its measured values (on the concentration curves) for a number of runs. The agreement is satisfactory with an error of less than 10% in most cases, the measured values themselves being subjected to errors of 5 or 10% due to the gradual rise of the concentration curves. It is noticed that the larger discrepancies in figure 12 occur when the nozzle is turned on, indicating that the atomising jet tends to disrupt the clear two-zone separation.

In conclusion, it can be said that several facts tend to confirm the T.S.P.F. as a valid model, except possibly for the presence of a deadwater region. It would be interesting to compare the total residence time τ as predicted by the A.D.P.F. and the T.S.P.F. models (Table 3). At low air velocities the latter model predicts higher residence time than the former, while the reverse is the case at higher air velocities. This would be explained by the presence of the deadwater region mentioned earlier at high velocities.

TABLE 3.3

Comparison of total residence times according to the A.D.P.F. and the T.S.P.F models.

Run	τ (A.D.P.F.) / s	τ (T.S.P.F.) / s
5a	16.3	17.6
9a	8.9	9.1
14a	4.0	3.9
17a	3.17	3.02
21a	1.73	1.70

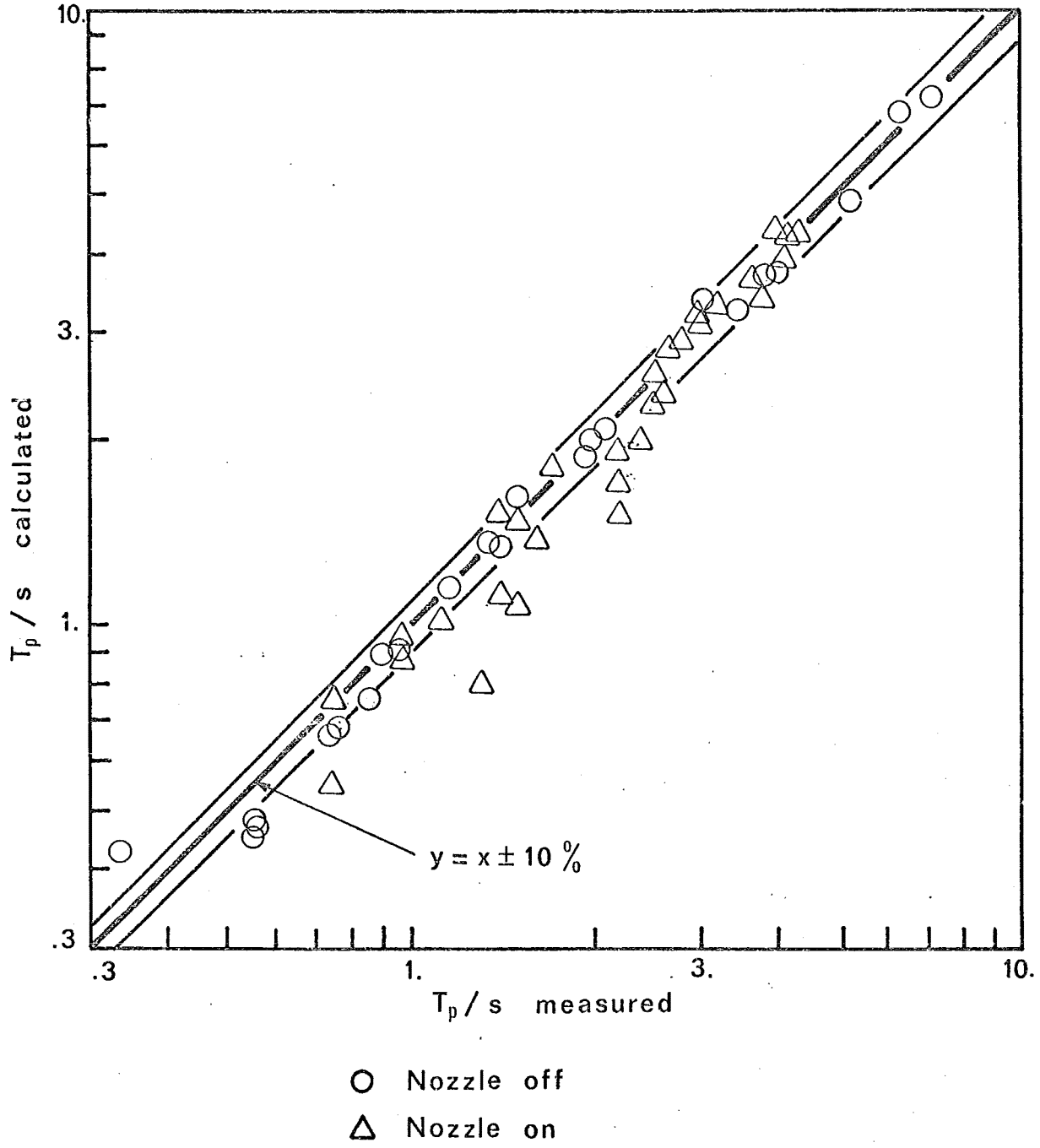


FIGURE 3.12 : CALCULATED VS MEASURED PLUG-FLOW TIME IN TSPF MODEL , DRYING AIR

(d) The dimishing-backmix model (D.B.M)

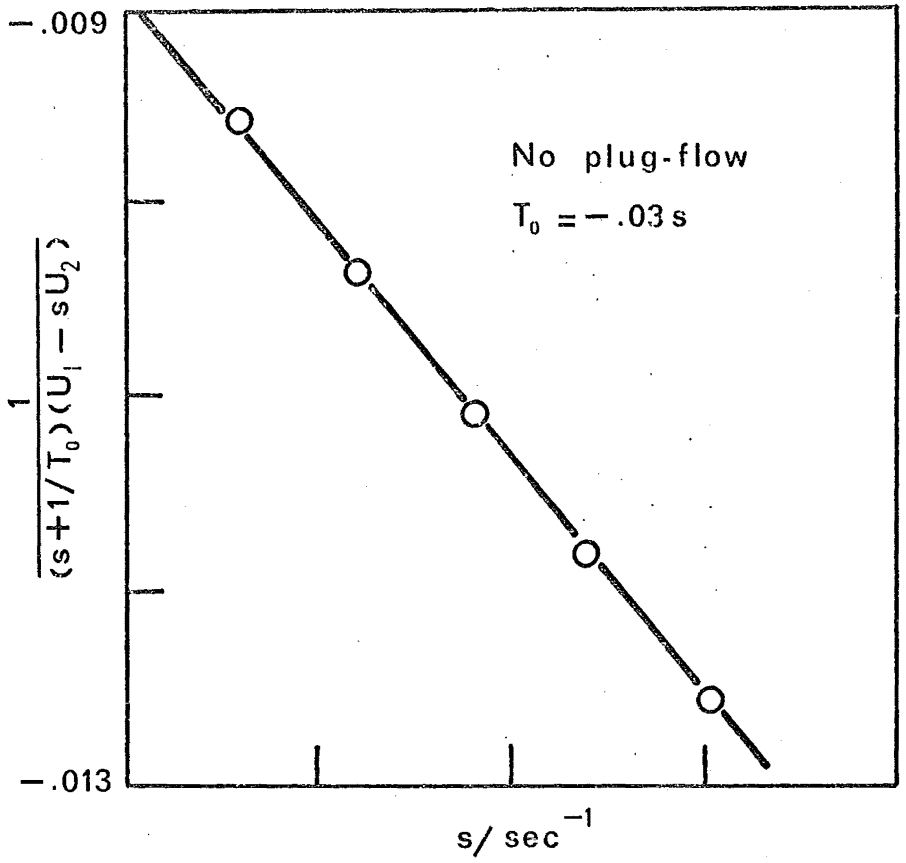
The D.B.M. model without plug flow was evaluated by plotting equation 104 of Chapter 2 (figure 13). The parameter T_o must be varied until the best straight line, as measured by the correlation coefficient, is obtained. (This was done automatically with a golden section subroutine on a computer.) Because one parameter is adjusted the method almost always gives good straight lines, but impossible values of the parameters result: T_o is found in many cases to be negative and k may be larger than unity. This clearly shows that the model must be ruled out.

The D.B.M. model with plug-flow (Chapter 2, equation 109) gives good results at high air flow rates (air velocities in excess of 0.3 m/s in the dryer) but fails at low air rates. Where it is applicable, the decay parameter k varies from 0.9 to 0.1 (k = 1 corresponds to pure plug flow), but no trend can be discerned as to the influence of either the drying air rate or the atomising air rate.

Since no significant improvement over the T.S.P.F. model can be found in spite of an extra adjustable parameter, the D.B.M. model was not subsequently used to characterise the flow although it still cannot be ruled out as a valid representation of the flow pattern, at least at high air velocities.

(e) The backflow-cell model with plug-flow in series (B.C.P.F.):

Equations 117 and 118 of Chapter 2 were plotted with U_1 replaced by $U_1 - T_p$, where T_p is adjusted to give the best straight line (figure 14). The range $s_T \simeq 1$ to 5 was used as consistent results could not be obtained in the lower s_T range (the results in that case being too sensitive to s_T). For the runs so analysed (Appendix 1) the values of the recycle b are small and distributed on both sides of



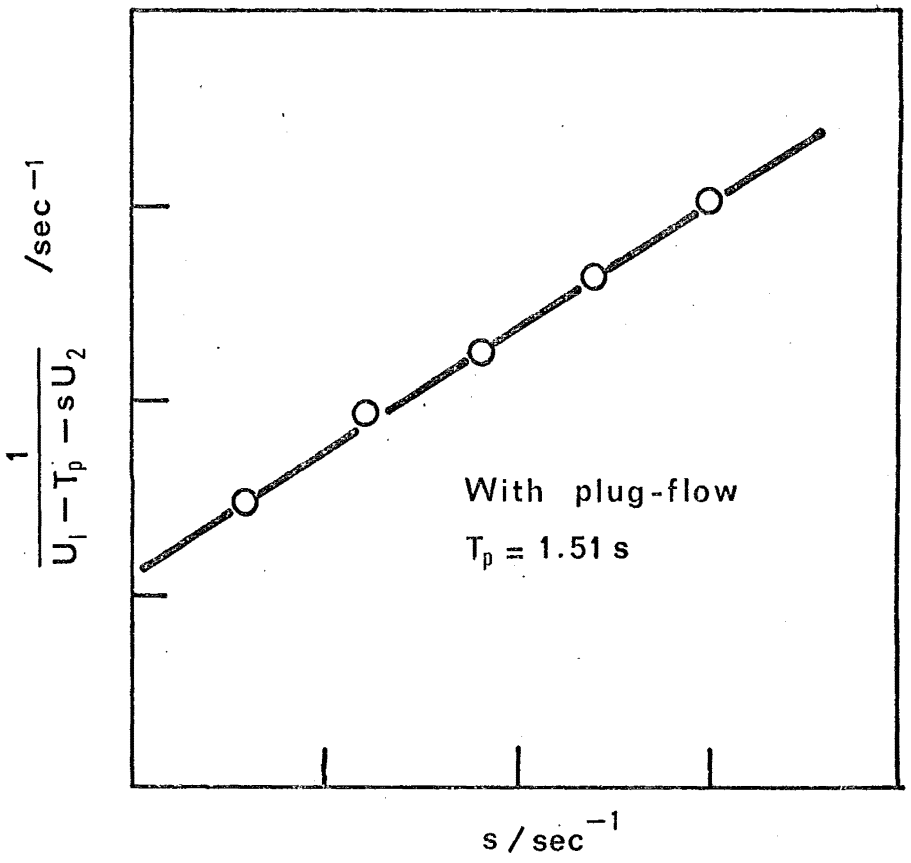


FIGURE 3.13: TRANSFER-FUNCTION ANALYSIS, DRYING AIR, DBM MODEL

Run 16a, air velocity = .61 m/s

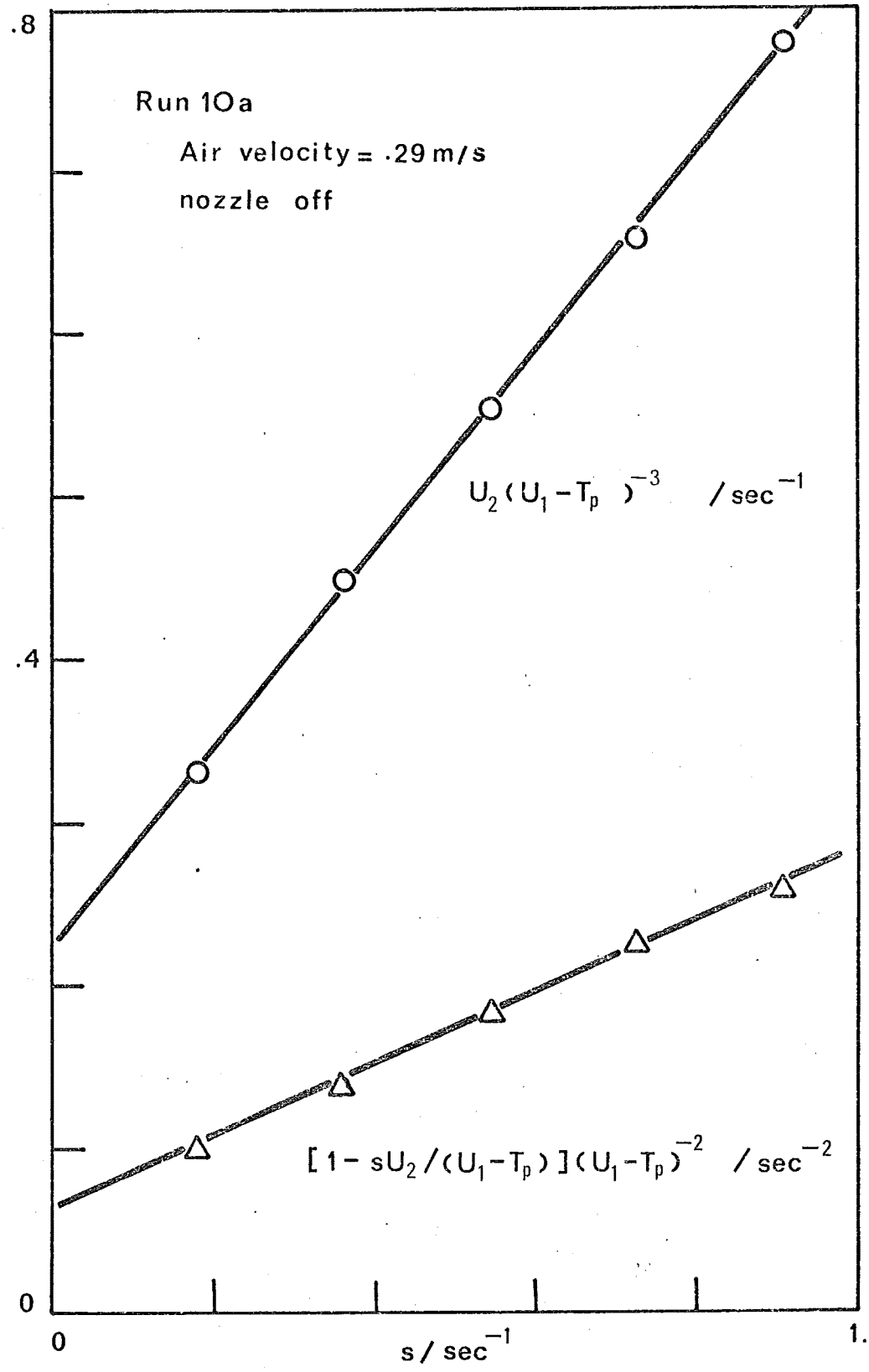


FIGURE 3.14: TRANSFER-FUNCTION ANALYSIS, DRYING AIR, BCPF MODEL

zero. Furthermore they are very sensitive to changes in T_p, a 5% difference in the latter causing in some cases a 0.2 change in b. A negative b indicates bypass, while b = 0 corresponds of course to the T.S.P.F. model. Therefore it was concluded that it is unnecessary to bring in the extra parameter b, and the T.S.P.F. model is sufficient.

V.1.4 Convolution of the response curves.

For the A.DP.F., T.S.P.F. and S.O.P.F. models, the impulse response (C-) curves are expressible analytically and can be convolved with the input concentration curve to give a predicted outlet response curve. Typical results for the first two models are shown in figure 15. The parameters for each model have been found by transfer-function methods. The results confirm what has been found by transfer function analysis, that the T.S.P.F. is the most accurate representation of the two.

V.1.5 Influence of the air velocity on the mixing pattern

(a) Average dispersion: It has already been pointed out that the Peclet number is a measure of the inverse of the average degree of backmixing or dispersion. In figure 16, Pe is plotted against the mean air velocity in the column, u, where u is found by dividing the length of the chamber by the holding time according to the T.S.P.F. model. Also plotted are Taylor's prediction (section II.1) and other workers' data for infinitely long pipes [L6].

The average degree of backmix is nearly insensitive to the air velocity, Pe has a mean value of 13.9. It may be thought that due to entrance effects Pe would be much lower than for infinite pipes. However this is not the case, the column Peclet number being slightly

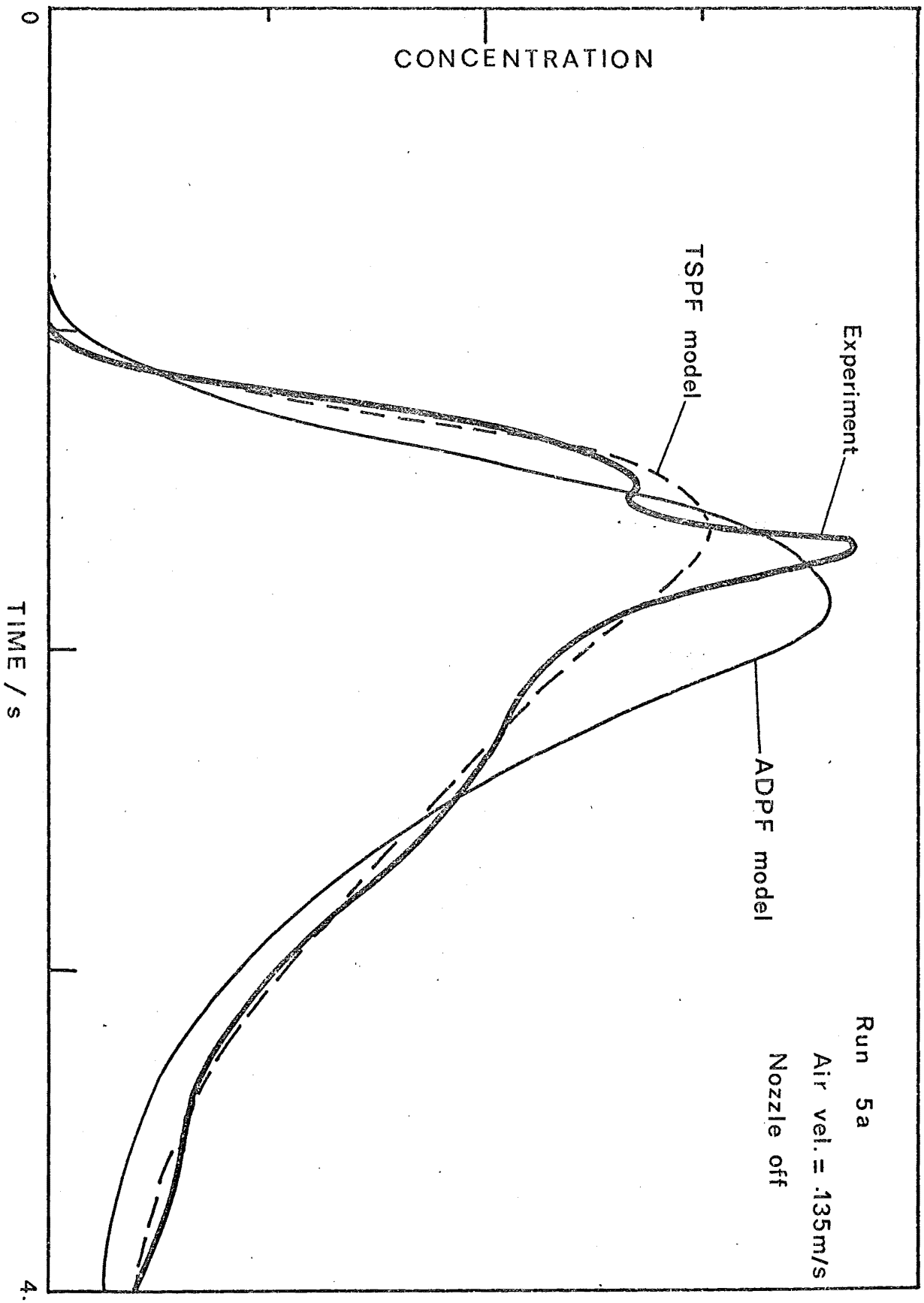


FIGURE 3.15 : CONVOLUTION OF DRYING AIR RESPONSE

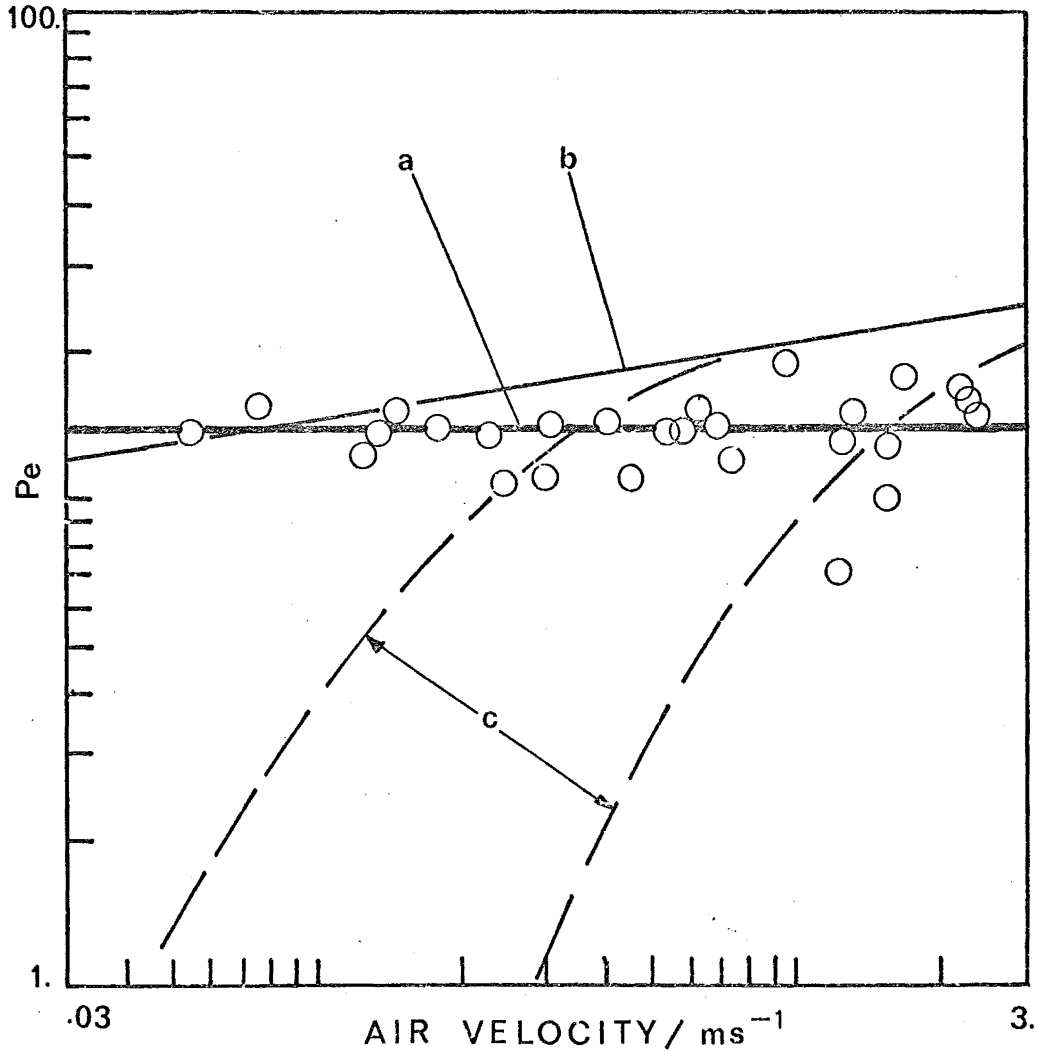


FIGURE 3.16: DEPENDENCE OF DRYING AIR-FLOW PECLET NO. ON AIR VELOCITY IN CHAMBER

(a) This equipment (nozzle off)

(b) Taylor's equation, ∞ pipes

(c) Previous data , ∞ pipes

lower than Taylor's prediction but higher than experimental infinite pipe values. The explanation is that when using the transfer function method one takes $s\tau \simeq 0.5 - 2$ so that less weight has been given to the tail, and the effect of any deadwater region exchanging slowly with the main flow has been minimised. Moment analysis and other standard methods can be considered as special cases of transfer function methods, with $s\tau = 0$.

(b) T.S.P.F. model parameters: The number of tanks, n, and the relative plug flow time, T_p/τ, are plotted against u in figure 17. n varies from 1 to 3 with an average of 1.9 . No influence of u can be observed on n .

The fractional values of this parameter may be difficult to relate to physical reality. Stokes and Nauman [S19] interpreted this as a series of tanks with some bypassing. The appearance of the response curve and the results of the backflow-cell model (negative recycle ratios b) seem to confirm this. Another explanation may be that the flow is stochastic (Chapter 2, section I.2.3) and the value obtained for n is simply an average of several flow states.

T_p/τ has an average value of 0.45. It appears to increase slightly as the velocity increases, to a maximum near $u \simeq 1$ m/s, then decrease again. Perhaps at low velocities the flow is inherently unstable, being near the transition point (see section IV.1.1), while at very high velocities the momentum of the "jets" of air from the inlet carries them further down and extends the stirred zone.

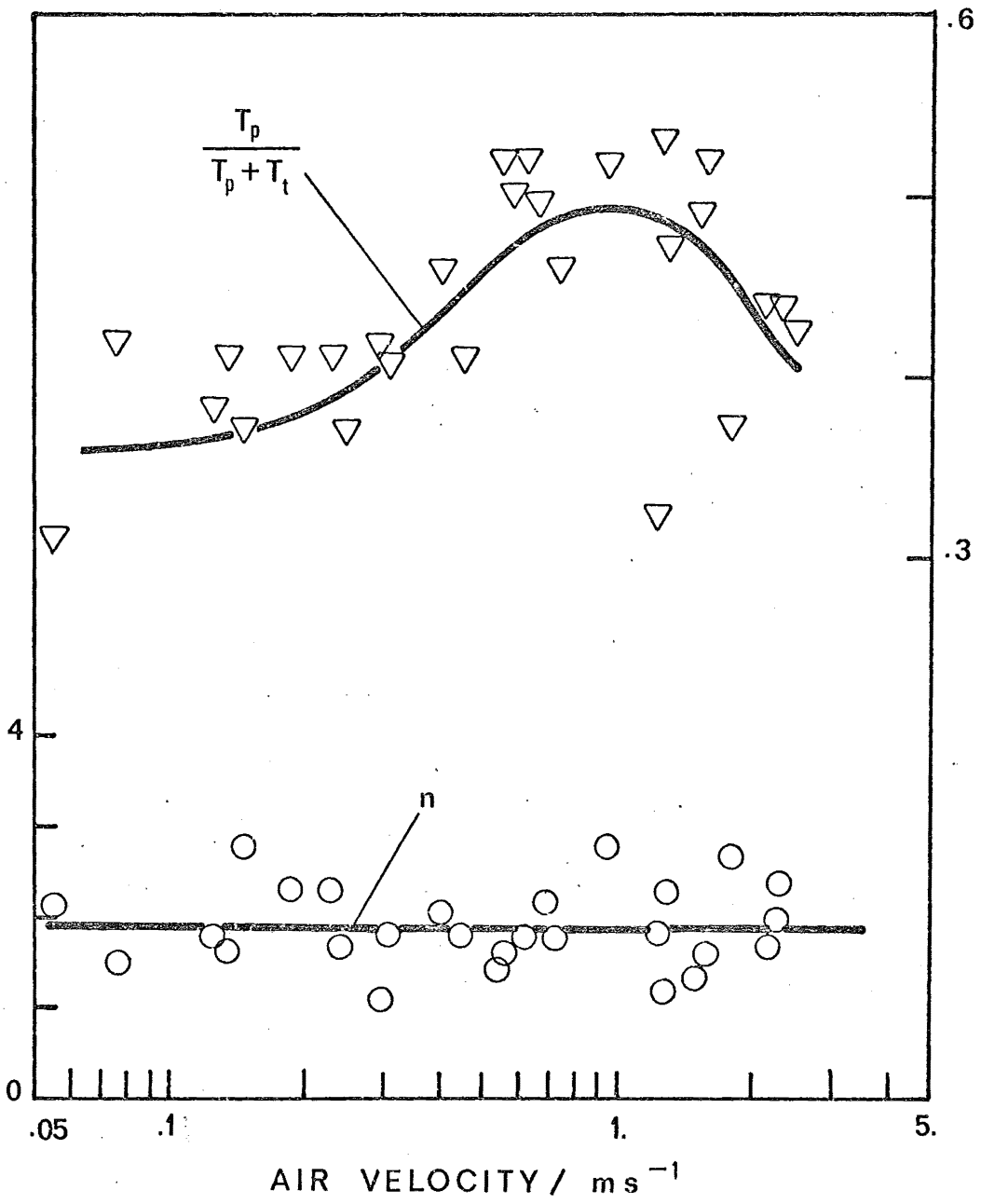


FIGURE 3.17: DEPENDENCE OF TSPF PARAMETERS ON AIR VELOCITY IN CHAMBER

V.1.6 Influence of the atomising air flow rate on the backmixing pattern

When the atomising air is turned on, a surprising effect is noticed: the Peclet number at first climbs sharply, sometimes to a value as high as 100, then decreases again to below its initial value. In figure 18, Pe/Pe_o is plotted against R_u, where Pe_o is the Peclet number at zero atomising air flow and R_u is the ratio of atomising air flow to main air flow. Pe/Pe_o reaches a maximum of 2.4 at $R_u = 0.018$.

How can the introduction of a disturbance drastically decrease the dispersion ? To find an answer, the T.S.P.F. parameters were plotted against R_u (figure 19). It can be seen that both n and T_p/τ have a maximum, although each takes place at a slightly different point: $R_u = 0.018$ for n, $R_u = 0.012$ for T_p/τ. Since the relative dispersion of this model is given by: (Chapter 2, section III.2.3)

$$\sigma^2 = U_2(0) \; / \; [U_1(0)]^2$$

$$= \frac{(1 - T_p/\tau)^2}{n} \qquad (3.25)$$

this would explain the trend in figure 17; the backmix region near the entrance is first broken up into small eddies which therefore decay more rapidly. However, as the atomising air rate increases further, it creates more turbulence and disturbance, and Pe decreases again (figure 20).

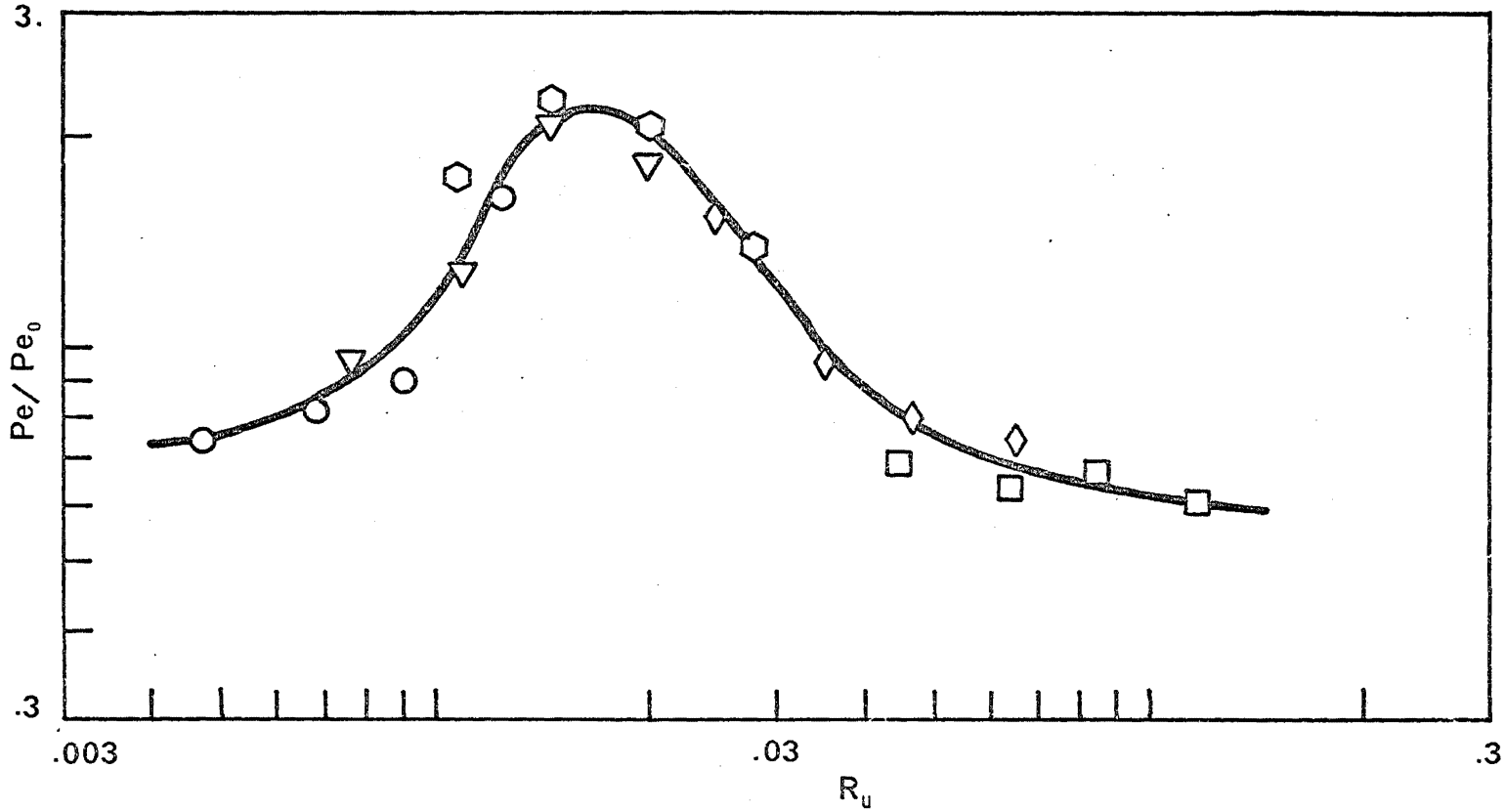


FIGURE 3.18: DEPENDENCE OF PECLET NO. ON THE AIR RATE RATIO R_u

	Run	Air velocity/ms $^{-1}$
□	5	.135
◇	9	.244
⬡	14	.54
▽	17	.69
○	21	1.27

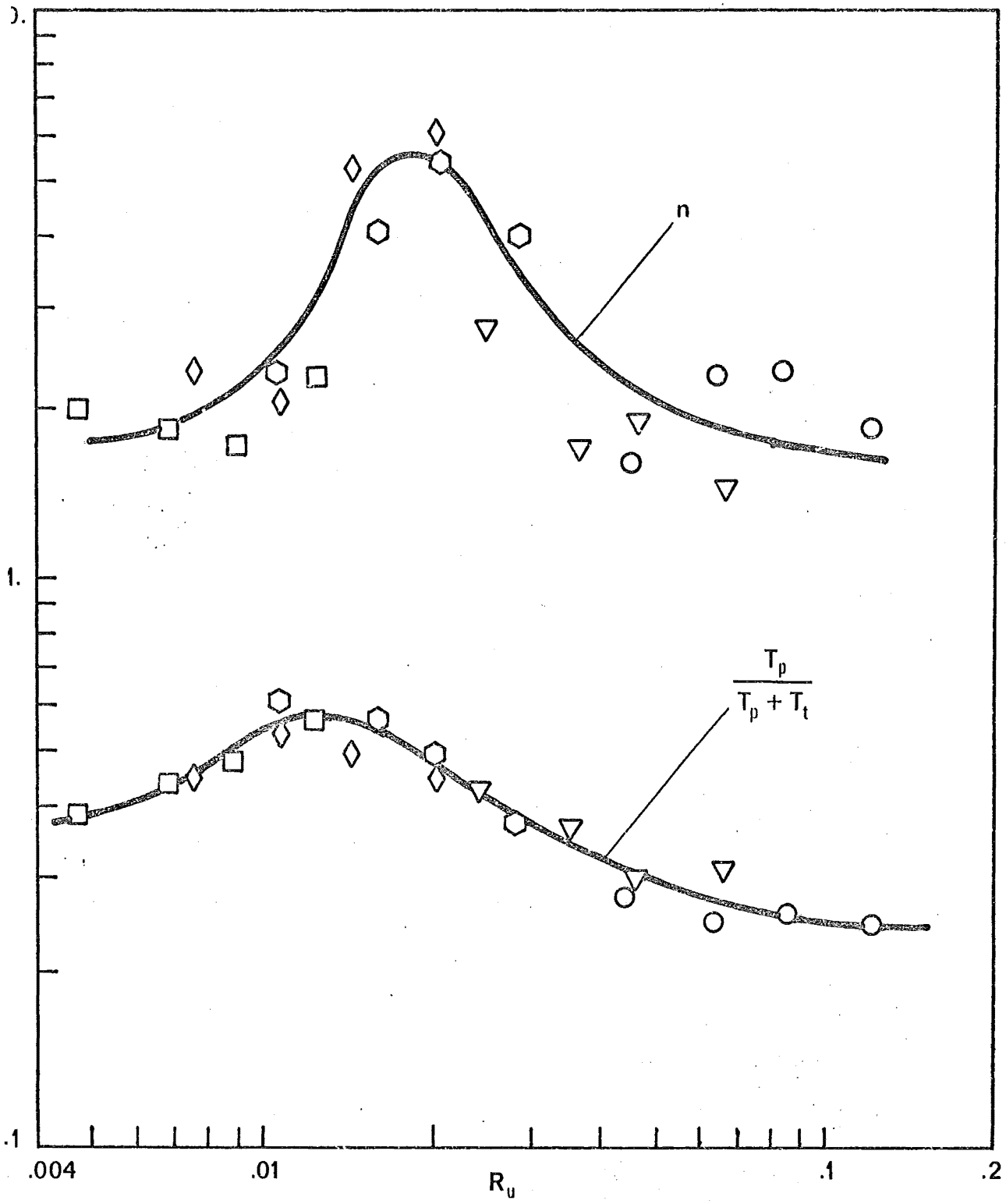


FIGURE 3.19 : DEPENDENCE OF TSPF PARAMETERS ON THE AIR RATE RATIO R_u

	Run	Air velocity /ms^{-1}
○	5	.135
▽	9	.244
⬡	14	.54
◇	17	.69
□	21	1.27

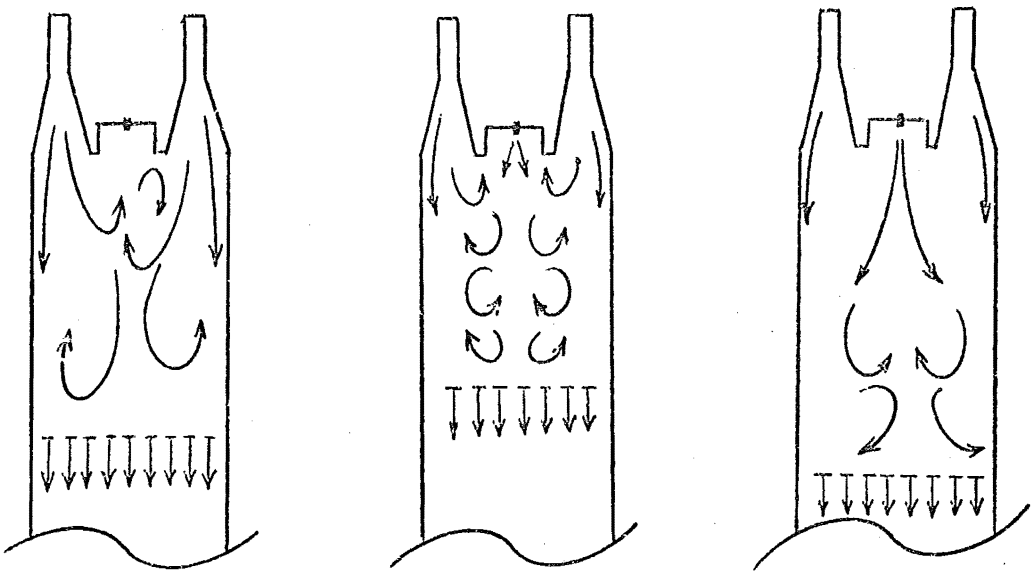


FIGURE 3.20 : PROPOSED EXPLANATION OF EFFECT OF JET ON BACKMIXING

The Craya-Curtet number at the minimum backmix point is (equation 10)

$$Ct = \frac{ru}{r_o u_o} = \frac{r_o}{R_u r}$$

$$= 0.25 .$$

The theory outlined in section II predicts a noticeable effect of the atomising jet as $Ct < 0.75$. In figure 19, n and T_p/τ start to rise at $R_u = 0.006 \pm 0.001$, i.e. $Ct = 0.74 \pm .15$. In view of the difference in geometries between the idealised model (figure 2) and the actual equipment, the agreement is surprisingly good.

V.1.7 Comparison of the drying air and the atomising air R.T.D.

So far only the drying air R.T.D has been described. This is because there is no qualitative difference between the R.T.D. of the two streams, both being best described by the T.S.P.F. model. A quantitative comparison of the mean residence time τ and the degree of backmix (as measured by Pe) is shown in Table 4. Because of fluctuations between runs at different R_u values, no influence of the latter has been observed, and only the mean results for all atomising air pressures have been tabulated.

Both the τ- and Pe-ratios are close to unity, and no trend can be observed as to the influence of the air velocity u . The residence time of the atomising air is slightly below that of the drying air, indicating that a jet zone does exist for the former, but only for a short distance (0.15 x 2200 mm = 300 mm at the most for run 10); certainly the range of τ-ratios (0.06 - 0.74) predicted by equation 19 is not to be found here.

In conclusion it can be said that the two streams merge quite early and become indistinguishable. The fluctuations in the value of the two ratios are much larger at low air rates, suggesting again the non-stationary nature of the flow in that range.

TABLE 3.4

Comparison of atomising air and drying air R.T.D's.

Run	τ ratio atom./drying	Pe ratio atom./drying
1	0.88 ± .20	1.00 ± .30
2	1.00 ± .10	0.89 ± .15
6	0.98 ± .06	0.80 ± .12
10	0.85 ± .02	1.03 ± .20
16	0.98 ± .18	0.94 ± .08
20	0.94 ± .10	1.26 ± .06

V.2 Velocity and turbulence measurements

The velocity and turbulence profiles, both radial and longitudinal, were measured for runs 5, 9, 14, 17, 21. There is no qualitative difference between them, and since run 14 straddles the minimum dispersion point, its results will be shown here.

The profiles were measured at 5 sections. At each section 24 points were probed, the DC voltage being integrated three times for 20 to 30 seconds each. The diameter traversed is at an angle of 12^{o} with the air inlets, i.e. almost directly below them. Three runs were made, at $R_u = 0$, 0.016 (near the minimum dispersion point) and 0.030 respectively.

Mean velocity profiles are shown in figure 21. The results are of limited accuracy due to the following factors:

(1) The non-parallel nature of the flow: the probes used were inadequate to discriminate effectively the component of flow being measured from other components. Also, the direction of the flow can only be guessed at.

(2) The influence of turbulence on the mean reading: when the turbulent component u' is small, its effect can be corrected for by [H13]:

$$\bar{u}_m \simeq \bar{u} \left(1 - \frac{1}{4} \frac{u_1'^2}{\bar{u}^2} + \frac{1}{2} \frac{u_2'^2}{\bar{u}^2}\right) \qquad (3.27)$$

where $\bar{u}_m$ is the measured value of $\bar{u}$, and the subscripts 1 and 2 denote the components parallel to and perpendicular to the main flow direction respectively. However, in this experiment $u_1'/\bar{u}$ is very large (up to 50%), u_2' is not known, the flow being anisotropic, and so the correlation cannot be made. Therefore the uncorrected values have been plotted on an arbitrary scale to give a qualitative picture of the flow.

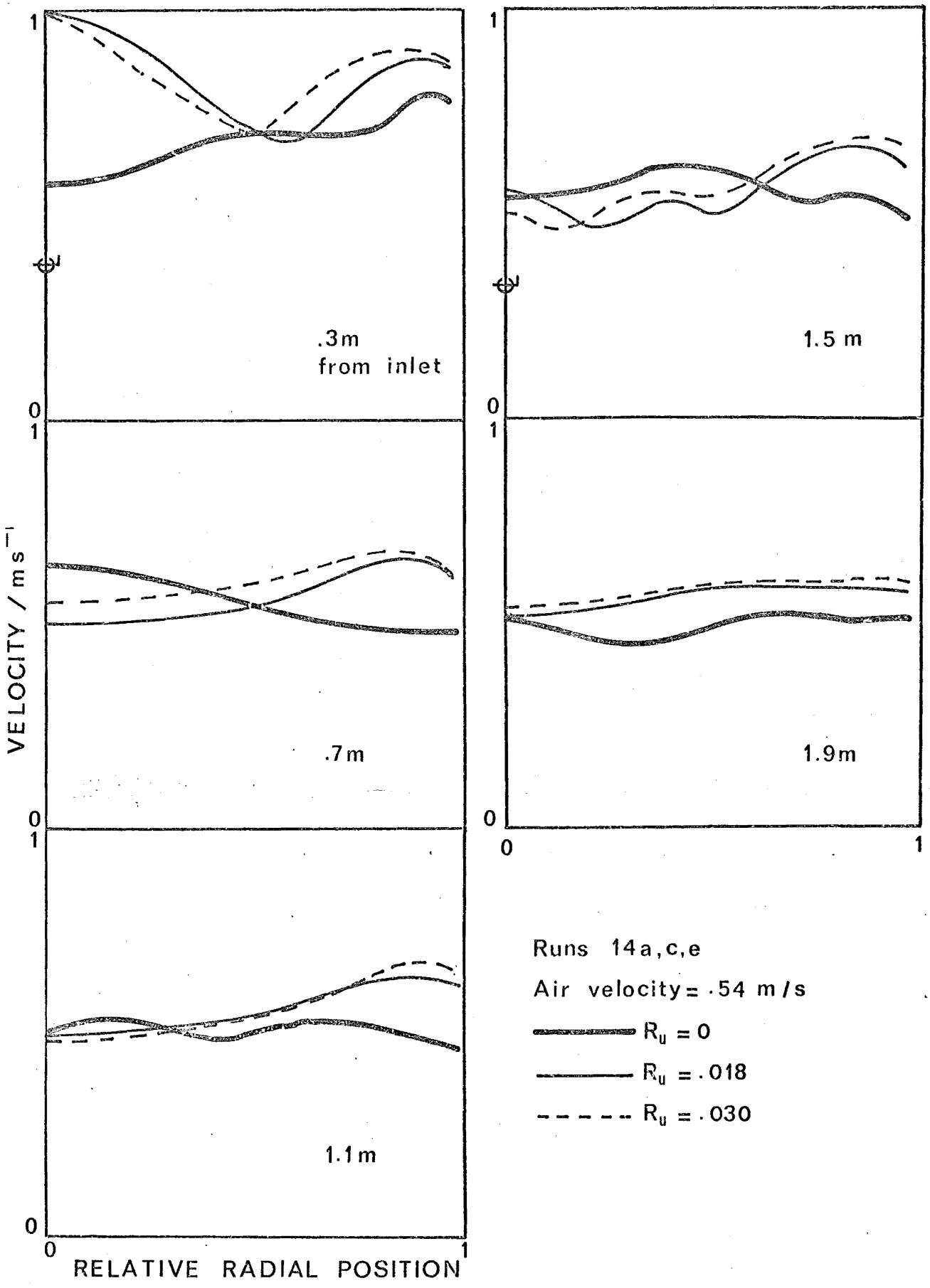
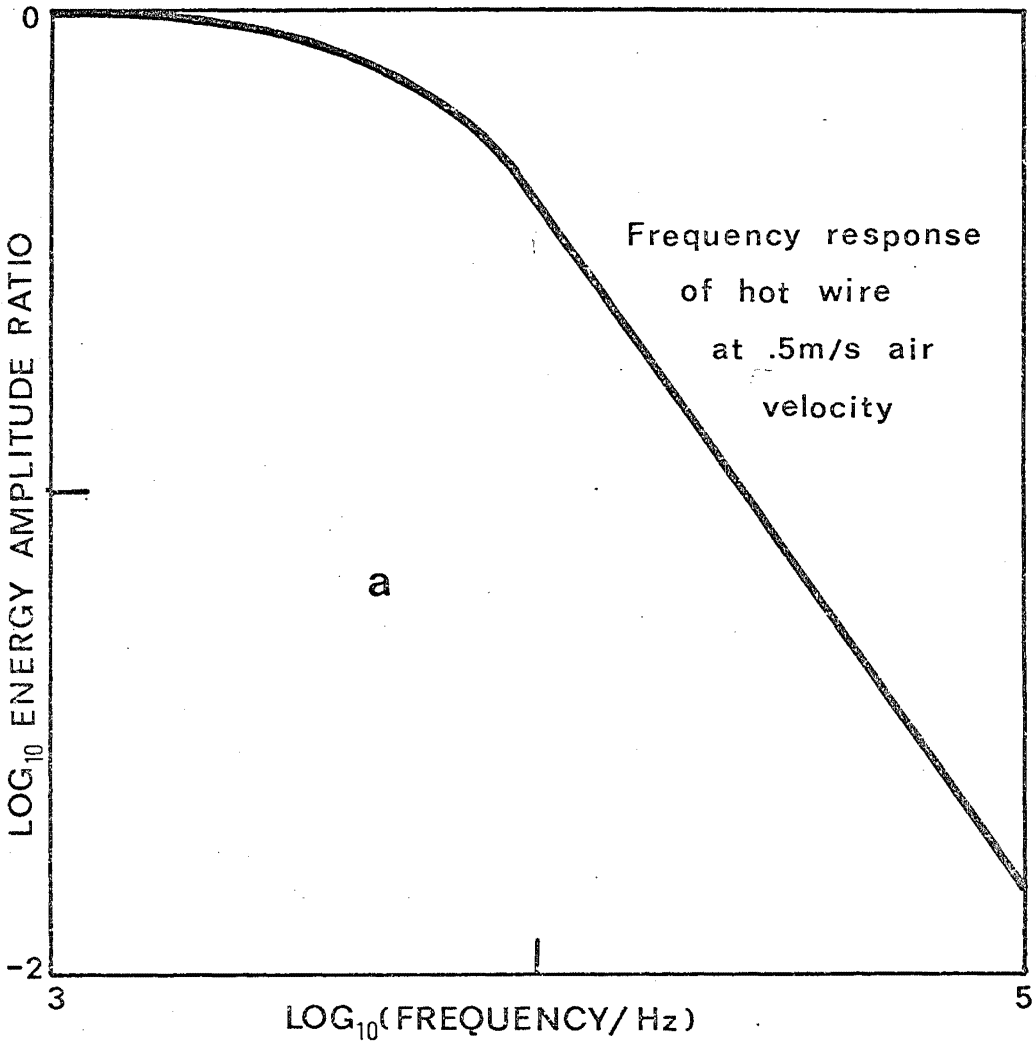


FIGURE 3.21: AIR VELOCITY PROFILES

Without the jet, a complex eddy system can be seen, extending far down the column. The jet reverses the flow profile drastically in the upper part of the column. However, a nearly two-fold increase of the atomising air rate makes little further difference to the profiles.

The spectra of turbulence for the 3 runs (again on an arbitrary scale) at a distance of 1.9 m from the inlet is shown in figure 22b. The spectra have been corrected for the frequency response of the instrument using graph 22a, which has been obtained by the method of section III.2. Similar spectra have been measured at 1.1 m from the inlet: at that point (not shown here) the three spectra are almost identical. Hence figure 22b shows that in run 14c the turbulence has decayed quicker than either in run 14a or run 14e. The small structures of turbulence are in all cases very close.

The longitudinal turbulence intensity profiles are plotted in figure 23. $\bar{u}/u'$ has been plotted in order to correlate the decay process as described by Taylor [T2, B10]. The turbulence decays slowly in the first 50-60% of the chamber, then much more quickly in the remaining 40-50%. This division corresponds quite accurately to that of the T.S.P.F. model. In the plug-flow part the energy input due to the stirring action of the entering air has stopped, so the decay must be more rapid. The presence of the atomising air jet accelerates the decay of turbulence, as seen by the steeper slopes of curves c and e in figure 23, presumably because it breaks up the eddy pattern near the entrance and decreases the scale of turbulence, hence increasing the energy dissipation [H13]. There is considerable uncertainty in curve 14c, indicating that the flow and decay pattern may be complex at the minimum dispersion point, a fact also borne out by R.T.D. analysis.



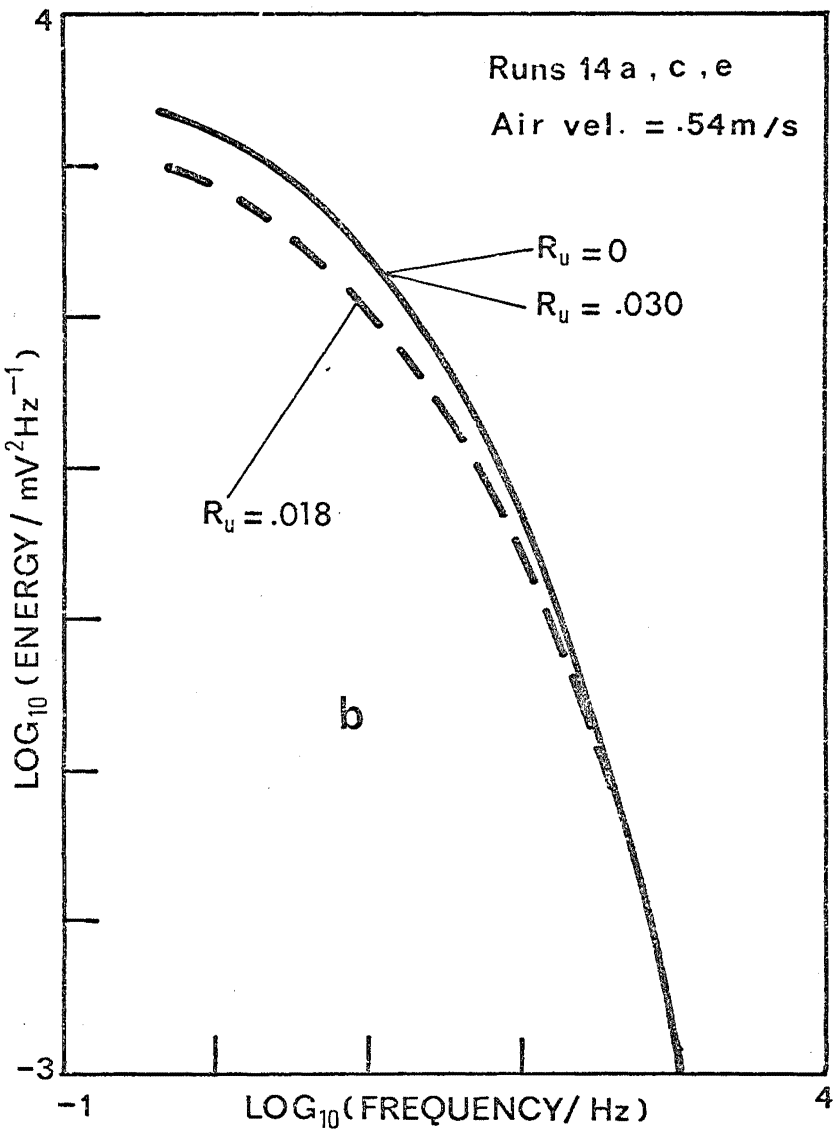


FIGURE 3.22: TURBULENCE SPECTRA

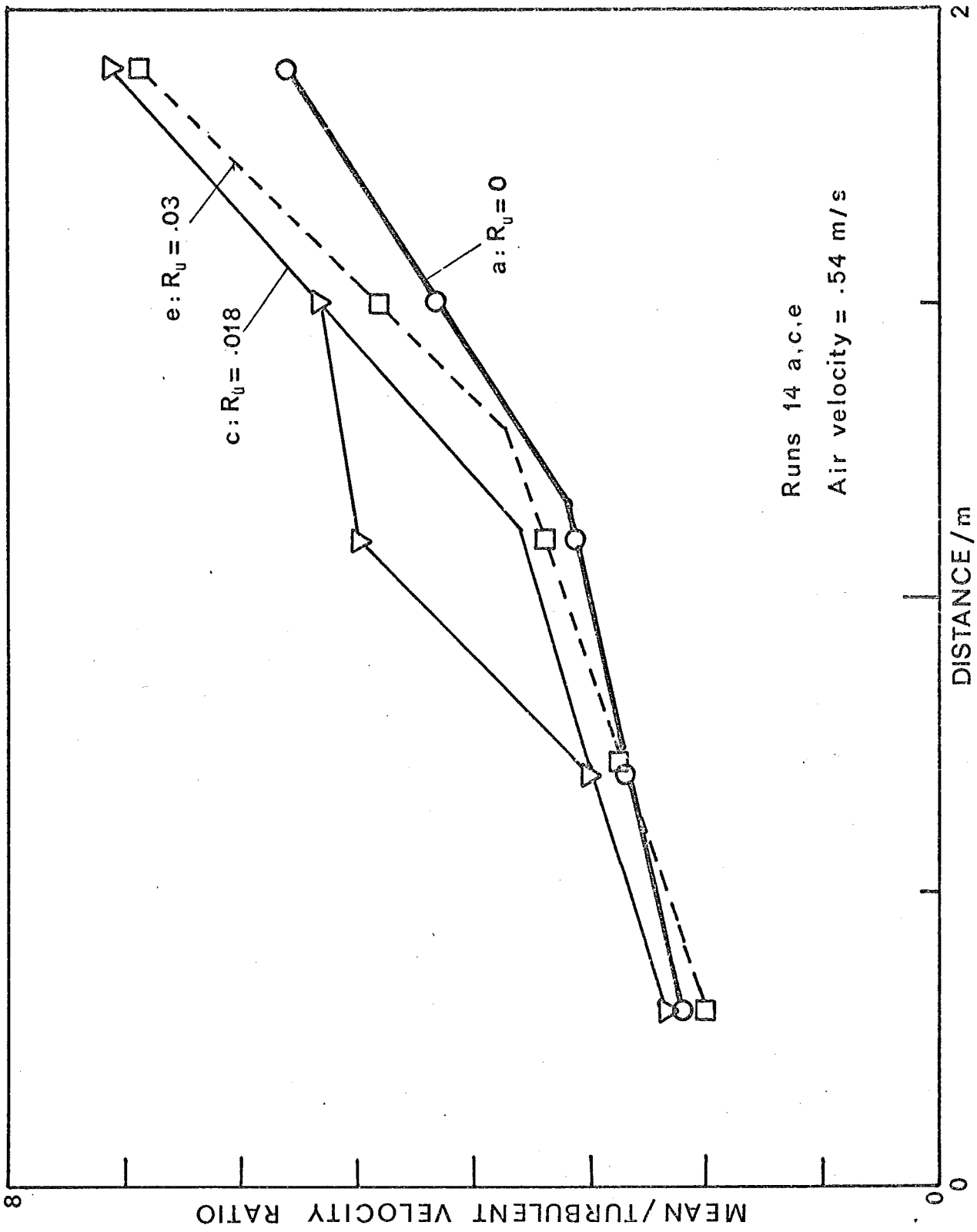


FIGURE 3.23: LONGITUDINAL TURBULENCE PROFILES

V.3 Flow visualisation results

More recently, smoke tests have been made by Uru [U2] on a similar 400 mm diameter column made of Perspex. He found two quite distinct regions in the chamber, - a well-mixed zone occupying the upper half approximately, and a parallel-flow zone, - the two zones being separated by a stable interface. He also found that the length of the plug-flow zone increases to a maximum then decreases again as the air velocity increases (figure 19). Thus the results of the transfer-function analysis are again confirmed.

VI. CONCLUSION

The transfer-function methods described in Chapter 2 are a promising way to process R.T.D. data. From simple and fast experiments valuable information can be obtained about the flow pattern in a vessel: backmix, bypass, recycle, plug-flow and non-stationarity can be detected. The analytical procedure used minimises tailing effects and does not require absolute values of concentrations to be known, so that sophisticated detection equipment is not necessary. The procedure dispenses with multivariable curve-fitting and gives direct visual information on the validity of the model used. Some care must be exerted in choosing the appropriate range of s; although a range $s\tau = 0.5 - 2$ was recommended by Michelsen and Østergaard [M12, M13], when a plug-flow region T_p is present, clearly a more appropriate range would be $s(\tau - T_p) = 0.5 - 2$.

For the spray dryer in question, the flow has been found to consist of a well-mixed zone (about two equal tanks in series, with a small amount of recycling and bypassing) in the upper half approximately, and a parallel-flow zone in the lower half. The flow is highly

unstable at low air rates, in the transition Reynolds number zone ($u < 0.3$ m/s). The atomising air jet has a large effect on the flow pattern, the degree of backmix in the vessel being governed by the Craya-Curtet number Ct. Minimum backmix occurs at $Ct \simeq 0.25$. The atomising air and the drying air appear in all cases to merge almost immediately upon entry.

This column and inlet design therefore offers desirable features from the process point of view, ensuring that the droplets and the air are well mixed immediately and thus increasing the evaporation (see Chapter 6), but then reverting to parallel flow in the lower part, where the particles are nearly dry and could be easily damaged by heat. This in turn suggests that if the problem of wall deposition can somehow be overcome, drying chambers with larger L/D ratios still would be desirable, especially for heat-sensitive products, as they would have a relatively longer plug-flow zone.

For spray dryers of this type, the most stable operating range would be:

(1) air velocity $\simeq$ 0.5 m/s - 1 m/s ($Re = 1.5 \times 10^4 - 3 \times 10^4$), where the plug flow zone has a maximum length and does not appear to fluctuate (figure 17).

(2) Ct (= column radius x mean velocity / nozzle radius x atomising air velocity) $<<$ 0.25 or $Ct > 0.74$, in which regions the flow pattern would not be too sensitive to small changes in the nozzle operating conditions, thus making process control easier. Only if it is essential to keep axial dispersion to a minimum, or when the atomising and drying air flow rates are not expected to fluctuate, should the region $Ct \simeq 0.25$ be used.

The results obtained in this chapter may also be applied to another type of spray dryer [K9] where a secondary air stream is

directed on the spray emerging from a pressure or rotary atomiser, thus ensuring good mixing. This arrangement, known as the "Czech concept", has been reported to increase the performance considerably. In this type of spray dryer, the air flow will also be influenced by a Craya-Curtet number based on the ratio between the primary and the secondary air flows.

NOTATION FOR CHAPTER 3

b recycle parameter in backflow-cell model, [-]

B anemometer wire constant, [$V^2\ s^{\frac{1}{2}}\ m^{-\frac{1}{2}}$]

c concentration of a tracer, [kg/m^3]

c_m concentration of tracer at the jet axis, [kg/m^3]

c_o concentration of tracer at the jet orifice, [kg/m^3]

D vessel diameter, [m]

g_{tr} (a.c.) transconductance of anemometer amplifier, [Ω^{-1}]

i current through anemometer probe, [A]

k_e entrainment constant of a jet, [-]

k decay coefficient, diminishing backmix model.

L vessel length, [m]

m mass, for example of tracer, [kg]

$\dot{m}$ mass injection rate, [$kg\ s^{-1}$]

n number of tanks, [-]

p bypass parameter in jet-stirred tank, [-]

r vessel radius, D/2, [m]

r_o jet orifice radius or inlet radius, [m]

r_j jet boundary radius, [m]

R_u atomising air to drying air rate ratio, [-]

R hot wire resistance, [Ω]

R_c cold wire (at fluid temperature) resistance [Ω]

R_o wire resistance at reference temperature, [Ω]

s Laplace transform parameter, [s^{-1}]

t time, [s]

$\bar{t}$ difference in first moments between outlet and inlet concentration curves, [s]

(Notation for Chapter 3, cont.)

T_o time parameter in diminishing backmix model, [s]

T_p plug-flow time, [s]

T_t total tank time, [s]

u air velocity, or drying air velocity, [m/s]

u' turbulent r.m.s. velocity, [m/s]

$\bar{u}$ mean air velocity, [m/s]

u_j effective jet carrying velocity, [m/s]

u_o jet orifice velocity, [m/s]

U_1, U_2 functions of s defined in Chapter 2.

v_t total fluid volumetric flow rate, [m^3/s]

V d.c. voltage, [V]

V' root-mean-square a.c. voltage, [V]

V_o d.c. voltage across the hot wire anemometer bridge at zero fluid velocity, [V]

x axial distance, [m]

y radial distance, [m]

α hot wire overheating ratio, $(R-R_c) / R_c$, [-]

β defined by equation 19b, [-]

π = 3.14159.

σ^2 difference in the 2nd moments of the outlet and inlet concentration curves divided by the squared difference in the 1st moments, [-]

τ holding time of vessel, [s]

τ_ω anemometer time constant, [s]

(Notation for Chapter 3, cont.)

Dimensionless numbers:

Ct Craya-Curtet number (equation 6)

Pe Peclet number, $Lu/\mathcal{D}$ where $\mathcal{D}$ is the axial dispersion coefficient.

Pe_D Peclet number based on diameter, Pe D/L .

Re Reynolds number, Du/ν where ν is the kinematic viscosity.

Sc Schmidt number, $\nu/\mathcal{D}_m$ where $\mathcal{D}_m$ is the diffusion coefficient.

CHAPTER 4

SPRAY RESIDENCE TIME DISTRIBUTION AND FLOW PATTERN

Chapter contents:

INTRODUCTION

To date the author knows of only two attempts to measure the disperse-phase residence time distribution in a spray dryer, both unpublished[C2, B9]. This may seem surprising, because information on this subject should be valuable for the determination of the air-spray mixing pattern and the degree of evaporation. Only if the spray R.T.D. is known can the performance of a dryer be accurately predicted (see Chapter 6). The reason for this lack of information is undoubtedly the experimental difficulties involved in sampling the dispersed phase at short time intervals and in detecting minute quantities of tracer. This chapter describes one such experiment using a radioactive tracer, as well as some speculative arguments concerning the degree of entrainment undergone by the droplets or particles, which may be useful in devising further experiments.

I. THEORY

I.1 Turbulence, entrainment and residence time distributions

"Entrainment" is the degree to which the particle motion tends to follow the fluid motion. Depending on the inertia of the particle, the viscosity of the fluid and the turbulence pattern of the fluid flow, the particles may either display plug-flow characteristics or have exactly the same R.T.D. as the fluid, but most often in spray-drying chambers an intermediate case will occur.

The effect of turbulence on the R.T.D. of a particle cloud is twofold: first, by imposing random motions on the particles, it will increase the axial and radial dispersion of the cloud; secondly, the drag and hence the settling velocity and mean residence time of the cloud will also be affected.

(a) Effect of turbulence or particle dispersion: According to the classical theory of turbulent diffusion (H13, F4, T2), the turbulent diffusivity of a cloud of particles, $\mathfrak{D}_p$, is related to its root-mean-square velocity fluctuation u_p' and its Lagrangian time scale t_{Lp} by

$$\mathfrak{D}_p = u_p'^2 \, t_{Lp} \quad . \tag{4.1}$$

As the particle inertia increases, u_p' decreases but t_{Lp} will change in an indeterminate manner. Soo and Perkins (S15) both predicted that $\mathfrak{D}_p$ will decrease with increasing particle inertia. Lilly (L9) carried out experiments with very small and very large particles and found that $\mathfrak{D}_p$ is equal to the fluid turbulent diffusivity in one case, and to zero in the other. This would seem to confirm Soo's and Perkins' theories, except that these are based on the assumption of very small particles which always stay within an eddy. Thus the state of the theory is still inadequate for calculating the dispersion of particles in a turbulent fluid.

(b) Effect of turbulence on the mean settling velocity: In Chapter 5 a review of this effect will be carried out, and it will be seen that in general an increase in the mean drag force will result from turbulence. Two effects (in gas-solid systems) are involved:

(1) A "Basset force" due to unsteady state of the flow field. In gas-solid systems, this force becomes important only at high energy dissipations (B1). Its magnitude cannot at present be predicted theoretically.

(2) An increase in the "effective" relative velocity u_{Re}. u_{Re}, which determines the Reynolds number and hence the drag coefficient c_D, is a combination of the mean relative velocity $\bar{u}_R$ and the

turbulent relative velocity u_R' . Since

$$\bar{F}_{Di} \propto c_D \, |u_{Re}| \, \bar{u}_{Ri}$$

where $\overline{F_{Di}}$ is the mean drag force and i denotes the i-th direction, an increase in u_{Re} will in general result in an increase in $c_D \, |u_{Re}|$ except in Stokes's regime, and thus an increase in $\overline{F_{Di}}$.

A quantitative criterion to determine the importance of this second effect will now be derived. Since the Basset force usually varies qualitatively in the same way as the increased effective relative velocity effect, this criterion will not be adversely affected by Basset forces. It will be assumed that:

(1) Turbulence effects are still slight, $u_R' \ll \bar{u}_R$ and $\bar{u}_R \simeq u_t$ where u_t is the terminal velocity of the particle in quiescent fluid.

(2) The mean and turbulent relative velocities can be combined vectorially:

$$u_{Re} = \sqrt{\bar{u}_R^{\,2} + u_R'^{\,2}} \tag{4.2}$$

$$\simeq \sqrt{u_t^{\,2} + u_R'^{\,2}} \quad . \tag{4.3}$$

For small values of u_R' as assumed before, the relative increase in the mean drag force $\bar{F}_D = c_D \, u_{Re} \, u_t$ will be:

$$R_D \simeq \frac{u'_R}{c_D u_{Re} u_t} \cdot \frac{d(c_D u_{Re} u_t)}{d(u_R')} \quad . \tag{4.4}$$

Let

$$c_D = a \, Re^{-n} \tag{4.5}$$

$$= b \, (u_t^{\,2} + u_R'^{\,2})^{-n/2} \tag{4.6}$$

where n has a local value on the drag curve corresponding to a relative velocity between u_t and $\sqrt{u_t^{\,2} + u_R^{\,2}}$ (n=1 for Stokes's regime, n=0 for Newton's law region).

From equations 6 and 4 :

$$R_D = \frac{(1-n)\ u_R'^2}{u_t^2 + u_R'^2} \tag{4.7}$$

There remains to evaluate u_R' . Friedlander[F6] showed that:

$$\frac{u_R'^2}{u'^2} = 1 - \frac{u_p'^2}{u'^2} = \frac{1}{1 + t_L/t_p} \tag{4.8}$$

where u' is the turbulent fluid velocity, t_L the fluid Lagrangian time scale, and t_p the particle time constant, defined in Stokes's regime by:

$$t_L \equiv \rho_p D_p^2 \ / \ (18\ \mu_f) \quad . \tag{4.9}$$

Friedlander results will be generalised to large particles by the use of a redefined time constant (see Chapter 5) :

$$t_p \equiv \frac{4\rho_p D_p}{3\rho_f c_D |\bar{u}_R|} \quad . \tag{4.10}$$

From the assumption of low turbulent relative velocity,

$$t_p \simeq t_{pt} = \frac{4\rho_p D_p}{3\rho_f c_{Dt} u_t} \tag{4.11}$$

where c_{Dt} is the terminal drag coefficient, and t_{pt} is independent of the turbulence.

Hence equation (8) becomes:

$$R_D = \frac{1 - n}{1 + \dfrac{u_t^2\ (1 + t_L/t_{pt})}{u_R'^2}} \quad . \tag{4.12}$$

For small particles, when Stokes's regime prevails, n=1, R_D=0 until $\sqrt{u_t^2 + u_R'^2}$ is large enough to make n differ significantly from 1.

When the assumption $u'_R << u_t$ does not hold, and Basset forces come into play, R_D is no longer a relative increase in drag force, but its value would hopefully provide some indication of how complete entrainment is. A more rigorous parameter could be derived, but it would still be based on untested theories and a detailed knowledge of the structure of turbulence, and may not be worth the effort.

I.2 The structure of turbulence in the present equipment

In order to apply equation (12) t_L must be known. In liquids it can sometimes be measured directly by high speed photography of neutrally buoyant particles[L8, K14]. Alternatively, u' and $\mathcal{D}_t$ (the diffusivity of a solute) can be measured separately and t_L calculated from an equation similar to (1).

There are, however, approximate relationships relating t_L to more conveniently measurable or calculable turbulence parameters such as u' , ε (the energy dissipation rate per unit mass), λ_g (the Eulerian lateral microscale) or L_f (the Eulerian longitudinal macroscale). From the definition of ε and λ_g it can be shown that:

$$\varepsilon = 15 \nu u'^2/\lambda_g \tag{4.13}$$

where ν is the fluid kinematic viscosity. For high turbulence Reynolds numbers $Re_\lambda \equiv u' \lambda_g/\nu$ (dominant inertial effects), Corrsin[C7] showed that:

$$\frac{\lambda_g}{\lambda_L} \simeq 5.4 \rho Re_\lambda^{-\frac{1}{2}} \tag{4.14}$$

$$\frac{\lambda_L}{u' t_L} \simeq 3 Re_\lambda^{-\frac{1}{2}} \tag{4.15}$$

where λ_L is the Lagrangian microscale, from which:

$$t_L = K_L u'^2/\varepsilon \tag{4.16}$$

and $K_L \simeq 0.9$.

Levins and Glastonbury[L8] found experimentally that $K_L \simeq 0.6$. Other investigators found it equal to 0.7 [A2], 0.33 [T4], while Hinze [H13] established that it must be of order 1. Therefore an average value $K_L \simeq 0.7$ seems reasonable:

$$t_L \simeq 0.7\ u'^2/\varepsilon \quad . \tag{4.17}$$

In the present equipment ε can be calculated as follows: the upper 55% of the drying chamber, up to x = 1.2 m, can be considered as a jet stirred tank (see Chapter 3), receiving energy from the entering air which is at a velocity of 64 $\bar{u}$ in the inlet pipes, where $\bar{u}$ is the mean air velocity in the dryer, and dissipating this energy within its volume. By means of an energy balance, it is easy to show that:

$$\varepsilon \simeq \frac{1700\ \bar{u}^3}{L_1} \tag{4.18}$$

where L_1 = 1 m, from which

$$t_L \simeq \frac{0.7\ u'^2\ L_1}{1700\ \bar{u}^3} = \frac{4 \times 10^{-4}\ IL_1}{\bar{u}} \tag{4.19}$$

where $I \equiv (u'/\bar{u})^2$ is the relative intensity of turbulence.

II. EXPERIMENTAL DETAILS

II.1 Material sprayed

In order to minimise and monitor any evaporation, a saturated solution of sodium chloride with traces of sodium dichromate - sodium hydroxide corrosion inhibitor was used in all runs. Microscopic examination of the droplets collected at the outlet showed no crystallisation, except for run E3 (Table 1) and hence it can be assumed that evaporation can be ignored except in that run.

II.2 Spray R.T.D. equipment and methods

II.2.1 Tracer and tracer injection

Carbon-14 in the form of a solution of sodium bicarbonate was used as a tracer. The solution is saturated with sodium chloride to avoid disturbing the feed properties. An amount of 10 - 50 µl of the solution, which has a specific activity of 1 mc/ml, was injected per pulse by means of a solenoid-operated 100 µl microsyringe (Figure 1). The nozzle was modified to permit the insertion of the syringe needle to within 5 mm of the nozzle orifice.

II.2.2 Droplet sampling equipment

The sampling equipment is shown in Figure 2. It consists of 40 brass cells, 6.35 mm diameter x 9.5 mm, placed at 8 mm centerline intervals in a half-cylindrical holder, and shielded by a 21 mm O.D. brass tube with a single 6.35 mm diameter hole at the top centre. The cell-holder has side grooves so that it can be guided along by pins in the shield. Each cell is covered by a slightly concave pad of Whatman glass filter paper, the purpose of which will be made clear later. As the cell holder moves, the cells pass successively under the hole in the shield, collecting each a small quantity of droplets on the filter paper.

The holder and cell assembly is pulled by a flexible cable wound on a 25.4 mm diameter spool, through a flexible-casing-type transmission. The spool is driven by a 1/4 HP motor acting through a reducing gearbox, and a continuously variable speed ratio gearbox, so that the spool speed varies from 0.2 to 1.8 turns/second and the cable speed from 16 to 145 mm/s approximately.

In order to have a degree of control on the size range of the

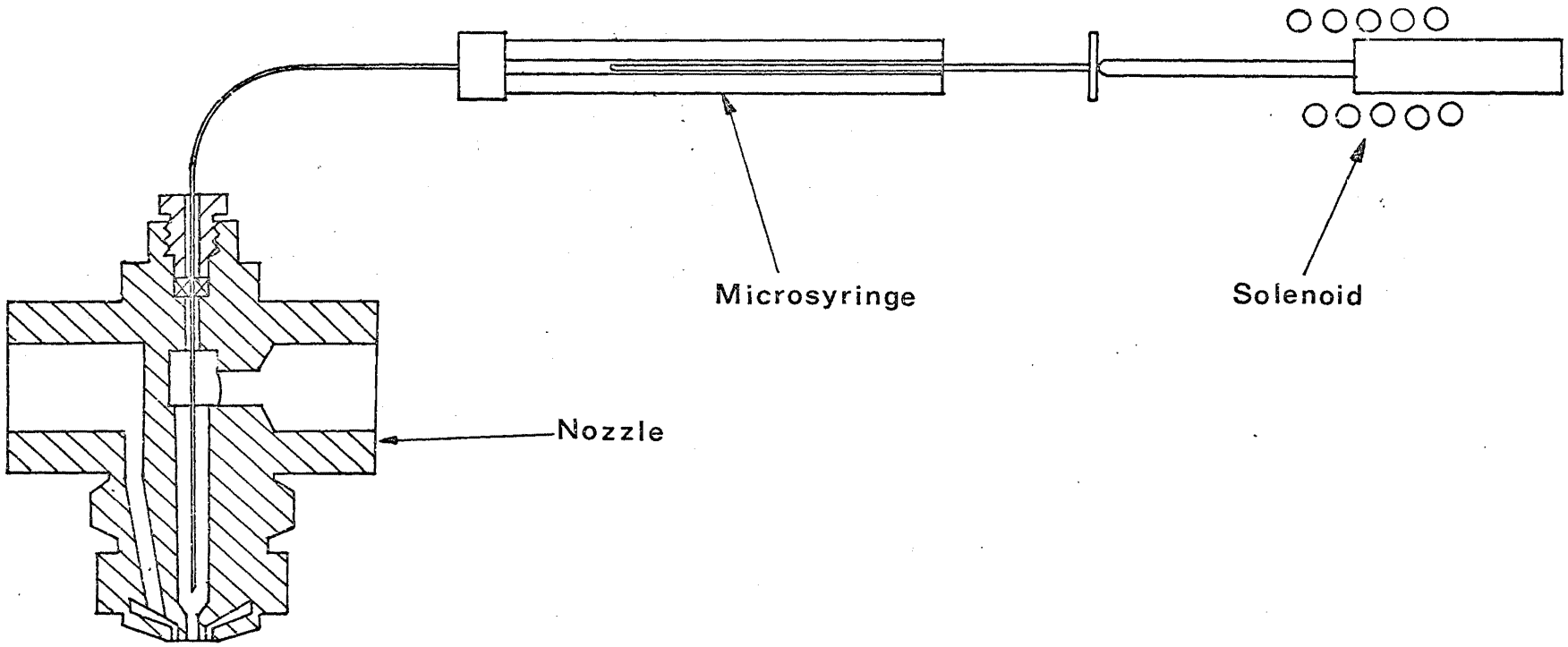


FIGURE 4.1 : LIQUID TRACER INJECTION EQUIPMENT

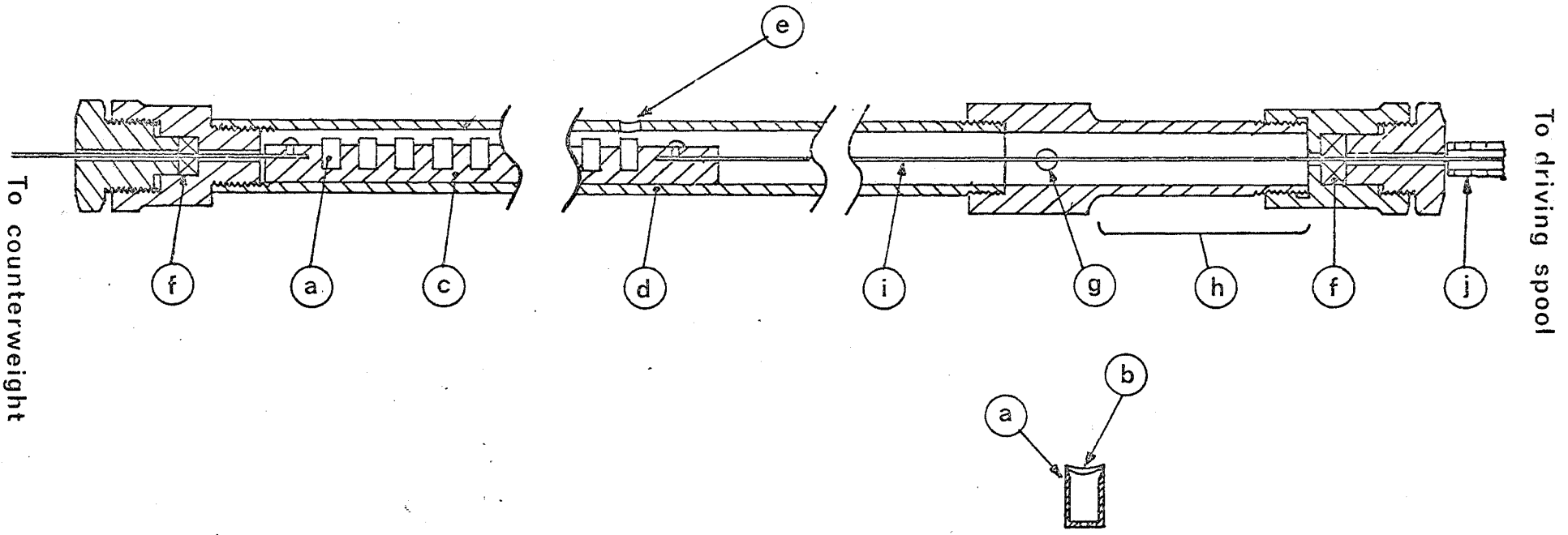


FIGURE 4.2 : TRAVELING DROPLET CATCHER

a	Collecting cell
b	Glass filter paper
c	Cell holder
d	Shield
e	6.4 mm hole
f	Packing
g	Perspex window for photoswitch
h	Stopping length
i	Cable
j	Flexible casing

droplets collected, the velocity of the air past the cylindrical droplet catcher is controlled by a funnel placed just above the catcher. The sizes of the funnels are given in Table 1.

II.2.3 Triggering and timing circuitry

A scaler counting in hundredths of a second determines the travel time of the cell holder between two given points, from a starting point to a photoelectric switch consisting of a beam of light shining on a CdS photoconductive cell. The circuit for triggering the injection, the sampler and the timer and stopping the last two is shown in Figure 3. As switch S.1 closes, it triggers the microsyringe solenoid and the motor, at the same time sending a "start" pulse to the scaler. When the photoelectric switch (CdS cell) is cut off, it activates relay R1 which opens switch S.3, stopping the motor, and closes S.2, sending a "stop" pulse to the scaler. The variation in the travel time for a given speed setting is less than ± 0.5 %. The start of the motor can, however, be delayed manually by opening the switch S.4.

II.2.4 Radioactivity measurement

The pads of glass filter paper impregnated with radioactive material are each put in a counting vial with 10 ml of scintillant and 2.5 ml of water. The scintillant used consists of 67 % by volume of Triton X-100 and 33% of toluene, the toluene having been premixed with 0.4% 2-5 diphenyloxazole (P.P.O) and 0.01% 1,4-bis(5-phenyloxazol-2-yl)benzene (P.O.P.O.P.). This mixture was introduced by Patterson and Greene[P5] and has been highly commended for ^{14}C counting [R2]. It has a complex phase diagram when mixed with water, first forming a clear solution, then an unstable suspension,

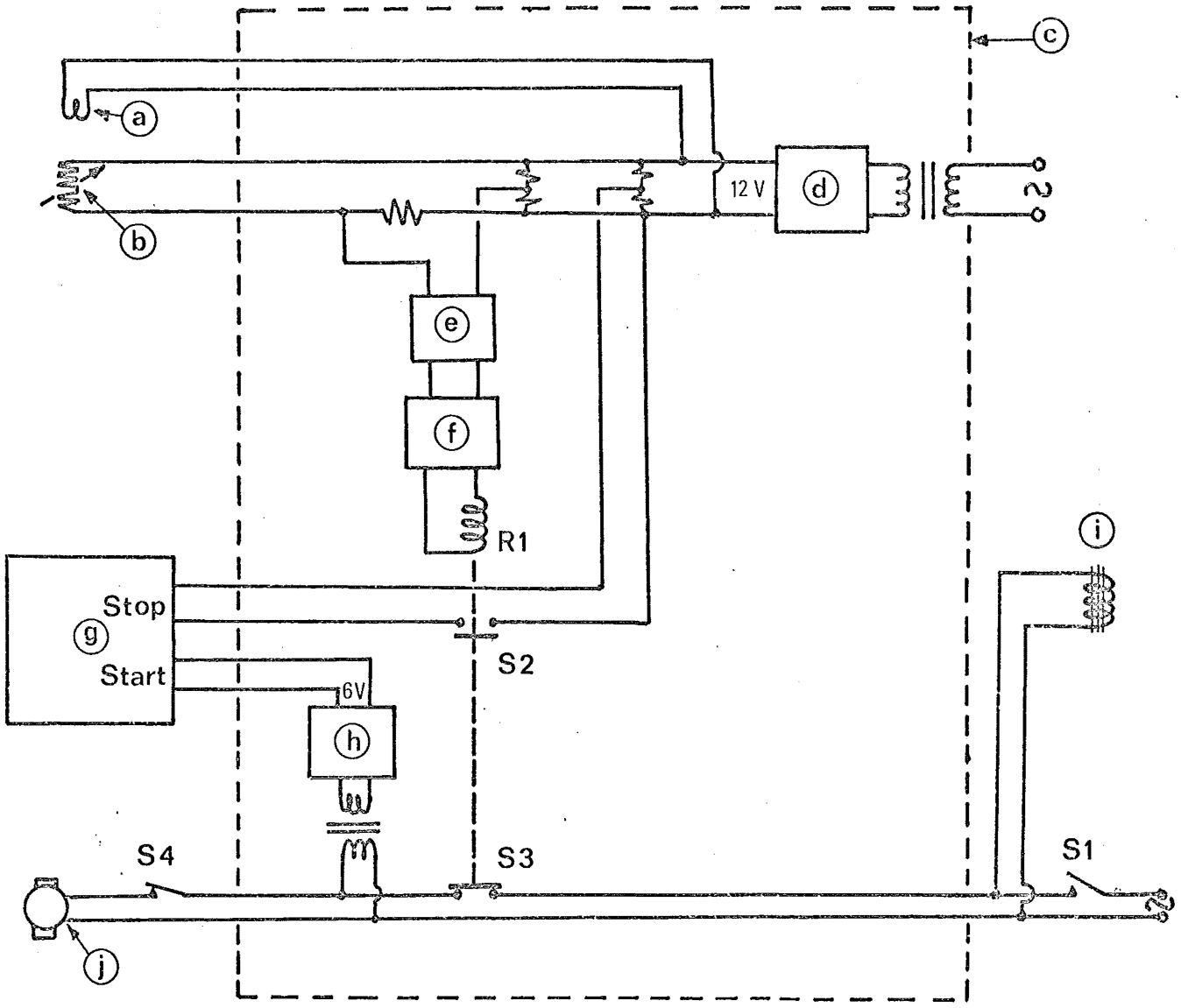


FIGURE 4.3 : TRIGGERING & TIMING CIRCUIT FOR SPRAY RTD MEASUREMENT

a 12V bulb
b CdS cell
c Control box
d Rectifier
e Amplifier
f Emitter follower
g Scaler
h Rectifier
i Microsyringe solenoid
j Droplet catcher motor

then a stable emulsion, and finally another unstable suspension as the water content increases. At the proportions given earlier the mixture is in the stable emulsion phase.

Each vial is vigorously shaken with a mechanical shaker for about two minutes, at the end of which the glass filter paper is disintegrated and suspended in the emulsion, thus achieving maximum dispersion of ^{14}C in the scintillant. The vials are then counted for β-radiation in a Unilux III automatic scintillation counter with two channels and coincidence circuit to eliminate background noise. The counting efficiency of each sample is determined by the channel ratio method and is about 80-90% for most vials. Detailed descriptions of the theory and practice of scintillation counting and other methods of radiation detection have been made by Price(P10, P11).

The standard deviation of a radioactivity count is equal to the square root of the total number of pulses counted. In this experiment the counting time was set to give a standard deviation of about 0.2% for the most active samples, i.e. a total count of about 2.5×10^5 pulses for these samples.

The vials were reused after being rinsed successively in methanol (using equipment similar to the one described by Harris and Friedman(H4)) and water, soaked for 24 hours in a 3% soltuion of Decon-90, and rinsed again with water. The background counts of the vials were checked before each run and were always insignificant compared with the activities measured. The brass cells were cleaned in a similar manner to the vials.

II.3 Droplet size measurement

For size measurements the droplets were collected in a rectangular perspex cell, 6.35 mm wide x 60 mm long, shielded in a hollow brass

cylinder of the same size as the travelling droplet catcher shield, and placed in the same position. The shield has a 6.35 mm wide slot which when passing over the cell (by a rotation of the shield) allows some droplets to fall in.

The cell contains a collecting fluid consisting of Shell Carnae-69 oil, which has been used by several other investigators (F2, R8, S13). Within one minute of sampling the droplets were photographed under microscope at a magnification of 60, together with an eyepiece grid which had previously been calibrated against a stage micrometer. After enlargement, the final magnification was 110. More details about the microphotography technique can be found in references (R8) and (S13).

The droplets were then counted and sized with a perspex grid divided into 9 size ranges (2, 4, 5.7, 8, 11.3, 15.5, 18.9, 22.6 and 27 mm). Between 1800 and 6000 droplets were counted for each run.

III. EXPERIMENTS PERFORMED

Liquid R.T.D. measurements were carried out at drying air rates corresponding to runs 1, 2, 6, 10, 16 and 20 of Table 3.1, Chapter 3. A summary of the operating conditions is shown in Table 1 below, together with the mass-median drop size results D_m for easy reference. It can be seen that 3 sets of nozzle operating conditions were used, giving a small droplet size range (run A1), a medium size range (run A2) and a large size range respectively (runs A3 to E3).

For each set of nozzle operating conditions, the "input concentration curve" was found by placing the droplet catcher 150 mm below the nozzle. This point is within the jet zone of the nozzle, where velocities are high, hence the shape of the concentration curve depends only on the tracer injection method and not on the drop size.

TABLE 4.1

Operating conditions for the spray R.T.D. experiments

Run No.	Corresponding air RTD run	Drying air velocity /ms^{-1}	Funnel outlet dia. /mm	Nozzle no.	Atomising pressure /kPa	Feed rate	Sampling time interval /s	D_m/μm
A1	1 & 2	0.055	25.4	1	380	0.21	0.514	15
A2	1 & 2	0.055	25.4	2	180	0.58	0.514	41
A3	1 & 2	0.055	25.4	2	180	1.33	0.514	90
B3	6	0.144	36.	2	180	1.33	0.513	125
C3	10	0.29	51.	2	180	1.33	0.513	63
D3	16	0.61	72.	2	180	1.33	0.355	94
E3	20	1.22	102.	2	180	1.33	0.208	(93)

For each of the runs listed, the funnel was installed, a small Pitot tube was placed under it at the spot where the travelling droplet catcher would be, then the air flow rate was adjusted to give a Pitot tube reading of 36 ± 2 mm of water (4.8 kPa) corresponding to a velocity reading of 24 m/s. Then the Pitot tube was removed and the travelling droplet catcher was inserted. In this manner the impact efficiences for the droplets are kept at the same value from run to run.

When residence times are high (runs A, B, C, D) each concentration curve must be measured in two or three overlapping segments. For each segment, 2 to 4 runs were done and measured separately. Each of these runs may consist of 1 to 25 samplings, in order to collect enough droplets in each cell to minimise random errors. The higher the air flow rate, the more samplings are needed to compensate for the small collecting cell area/total flow area ratio and the reduced cell exposure time.

IV. RESULTS AND DISCUSSION

IV.1 Droplet sizes

Droplet sizes results are shown in Table 2. For run E3 no measurement was taken because the flow past the collecting cell was extremely unstable, and droplets tended to come in dense swarms and merge on impact with the collecting fluid. An average value of the results of other runs (A3 to D3), D_m = 93 μm, will be used for subsequent calculations.

TABLE 4.2

Droplet size results

Run \ Size/μm	Number of droplets									D_m/μm
	5 to 9	9 to 25.5	25.5 - 43	43 - 61	61 - 86	86 - 119	119- 154	154- 186	186- 223	
A1	3265	70	0	0	0	0	0	0	0	15
A2	2757	434	98	26	2	0	0	0	0	41
A3	955	385	183	115	62	19	5	1	0	90
B3	1848	455	189	130	94	30	17	8	3	125
C3	1929	428	137	74	15	6	0	0	0	63
D3	4546	2037	679	467	271	70	28	9	0	94

IV.2 Entrainment parameters

The parameters u_t, n, t_{pt}, R_D and others related to entrainment are shown in Table 3 for later reference. The fluid turbulent velocity u' cannot be determined accurately, as it varies considerably within the well mixed zone, and a mean value u'/u = 0.4 (I = 0.16) was used for all runs.

The value of n was taken at a mean value of the Reynolds number between u_t and $\sqrt{u_t^2 + u_R'^2}$. It was determined from the equation:

$$c_D = \frac{24(1 + 0.1\ Re)}{Re} \tag{4.20}$$

which describes the drag curve between Re = 0.4 and Re = 2 (Chapter 5). From this equation,

$$n \equiv - \frac{d(\ell n\ c_D)}{d(\ell n\ Re)}$$

$$= \frac{1}{1 + 0.1\ Re} \tag{4.21}$$

TABLE 4.3

Entrainment parameters

Run	$D_m/\mu m$	u_t/ms^{-1}	t_{pt}/s	$\bar{u}/ms^{-1}$	u'/ms^{-1}	t_L/s	u_R'/ms^{-1}	n	R_D
A1	15	0.007	$7x10^{-5}$	0.055	0.022	$1.2x10^{-3}$	0.005	1.0	0
A2	41	0.05	$5.5x10^{-4}$	0.055	0.022	$1.2x10^{-3}$	0.012	0.9993	$4.x10^{-5}$
A3	90	0.22	$2.2x10^{-2}$	0.055	0.022	$1.2x10^{-3}$	0.021	0.88	0.001
B3	125	0.37	$3.8x10^{-2}$	0.144	0.058	$4.4x10^{-4}$	0.058	0.76	0.006
C3	63	0.12	$1.\ x10^{-2}$	0.29	0.12	$2.2x10^{-4}$	0.12	0.943	0.028
D3	94	0.23	$2.3x10^{-2}$	0.61	0.24	$1.0x10^{-4}$	0.24	0.85	0.08
E3	(93)	(0.23)	$(2.3x10^{-2})$	1.22	0.49	$5.2x10^{-5}$	0.49	0.81	0.16

IV.3 Droplet residence time distribution

IV.3.1 Input pulses

The input pulses for nozzle operating conditions no.2 (run A2) and no.3 (runs A3-E3) were found to be virtually perfect δ-pulses, dropping to near zero as early as the second cell (t = 0.066 s).

The input pulse for nozzle operating condition no.1 (run A1) has a first moment of 0.58 ± .03 s and a second moment of 0.29 ± .07 s^2, which are low compared to the moments of the outlet concentration curve (21 s and 71 s^2 respectively).

IV.3.2 Output pulses

All the averaged output pulses are plotted in Figure 4. Numerical data can be found in Appendix A. The atomising air R.T.D.s under the same operating conditions are also plotted for comparison.

An outstanding feature is the large and often regular fluctuations present in most curves. In run A1 for example, these fluctuations have a period of about 7 s. Several factors may have caused these fluctuations:

(1) Radiation counting errors.

(2) The small number of the droplets collected in each cell.

(3) Eddies or instability in the droplet flow.

Factor (1) may be discounted, the counting procedure having been checked by repeated measurement, and the counting times being large enough to keep the errors below 1% in most cells.

Factor (2) is due to the fact that quantities, and not concentrations, of tracer are measured. Hence the apparent "concentrations" depend in fact on the number of droplets collected in each cell. This number is calculated to be between 750 and 7200 droplets for each point on the curve. Assuming that this quantity follows a Poisson distribution,

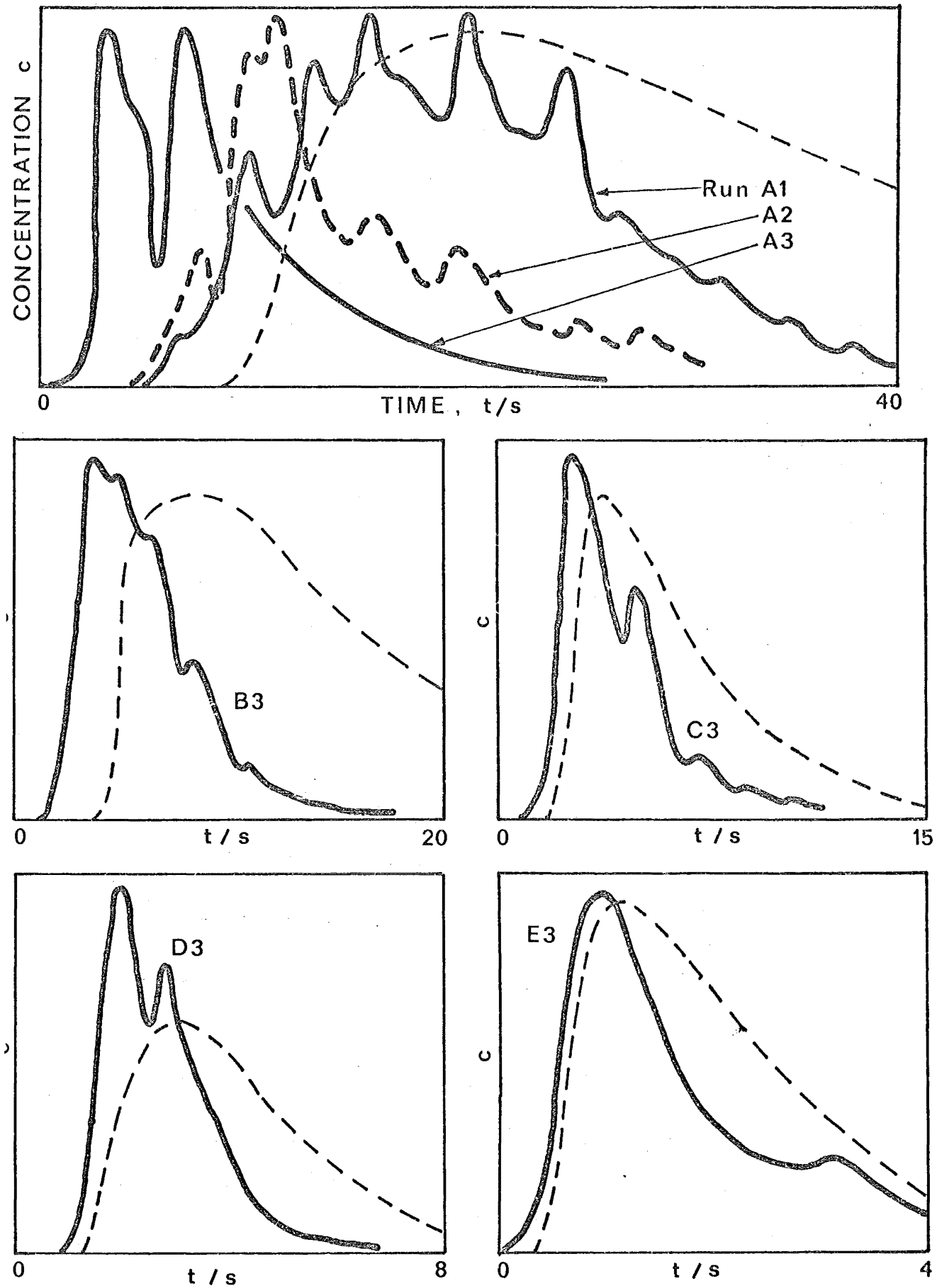


FIGURE 4.4: SPRAY OUTLET TRACER CONCENTRATION CURVES

the standard deviation would then be 3.5% to 1% (the upper limit applies to run E3, the lower to run A1). Although fairly large, this error can only explain the random fluctuations from cell to cell and not the slow and systematic fluctuations observed, each of which may encompass more than 10 cells.

Therefore it must be concluded that either true eddying or unsteady state is occurring in the flow of the droplets, especially at fine and medium droplet sizes (runs A1, A2).

Run A3 (low air velocity, large droplet sizes) shows a pronounced bimodal (two peak) response curve, peaking at 3.6 and 6.7 s respectively. Run A2 (medium droplet sizes) shows the same feature although less markedly. The first peak is probably due to a bypass, the momentum of the larger droplets carrying them right through the well mixed zone. Less heavy droplets, or those on the boundary of the jet, are caught in the air turbulence and slowed down. At higher air velocities, the response curve is generally unimodal, indicating that no significant bypassing occurs.

IV.3.3 Transfer function analysis

Only the axially-dispersed plug flow (A.D.P.F.) and the tanks-in-series-and-plug-flow (T.S.P.F.) models were analysed (Table 4), since the lack of accuracy does not justify models with more parameters.

The graphs for the transfer function analysis are shown for all runs in Figure 5. It can be seen that the T.S.P.F. model is not as good as the A.D.P.F., probably because of the lower degree of turbulent motion undergone by the droplets, as well as to the velocity distribution of the droplets resulting from the drop size distribution (section IV.3.4).

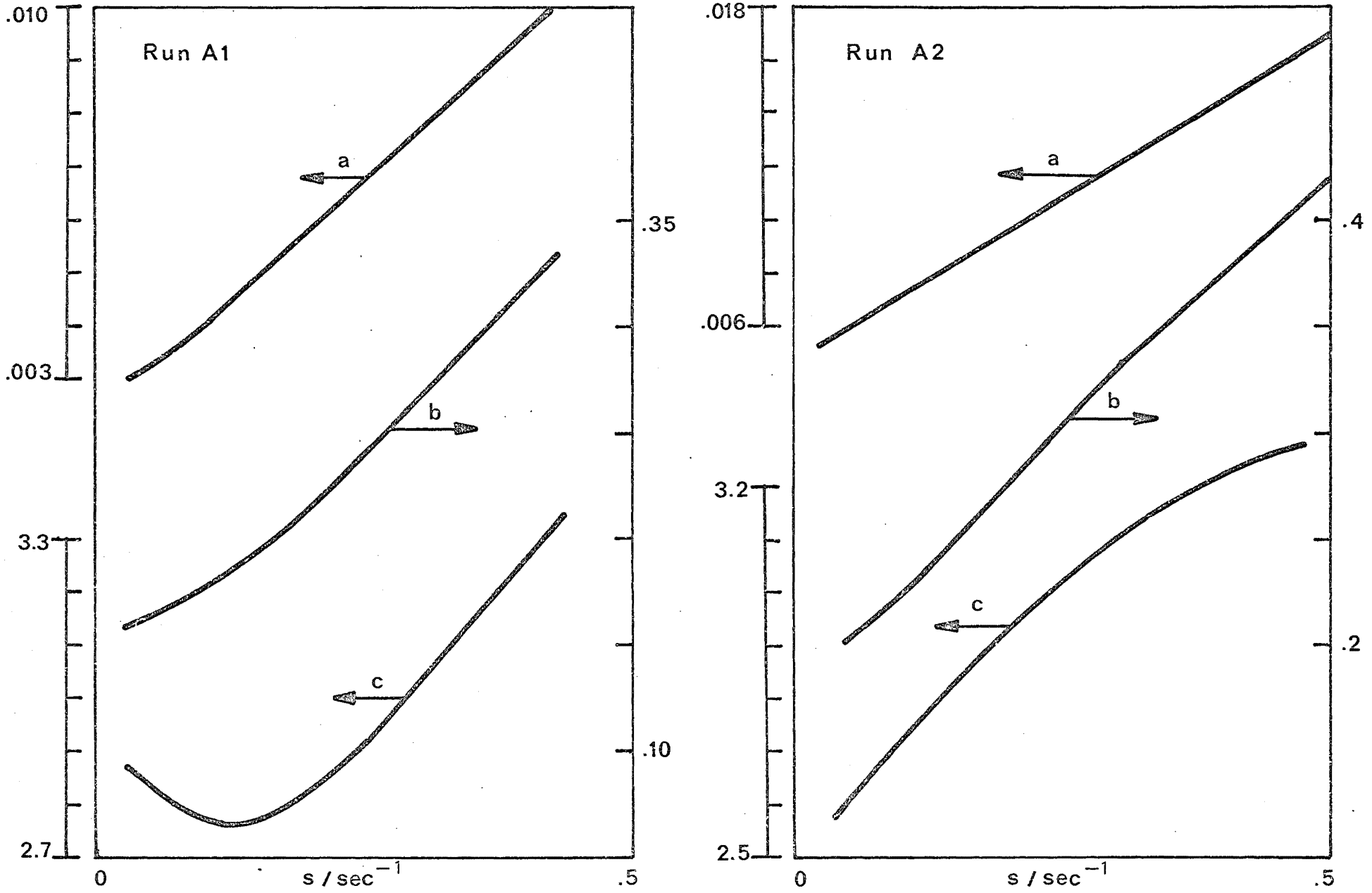


FIGURE 4.5 : TRANSFER-FUNCTION ANALYSIS FOR SPRAY RTD, ADPF & TSPF MODELS

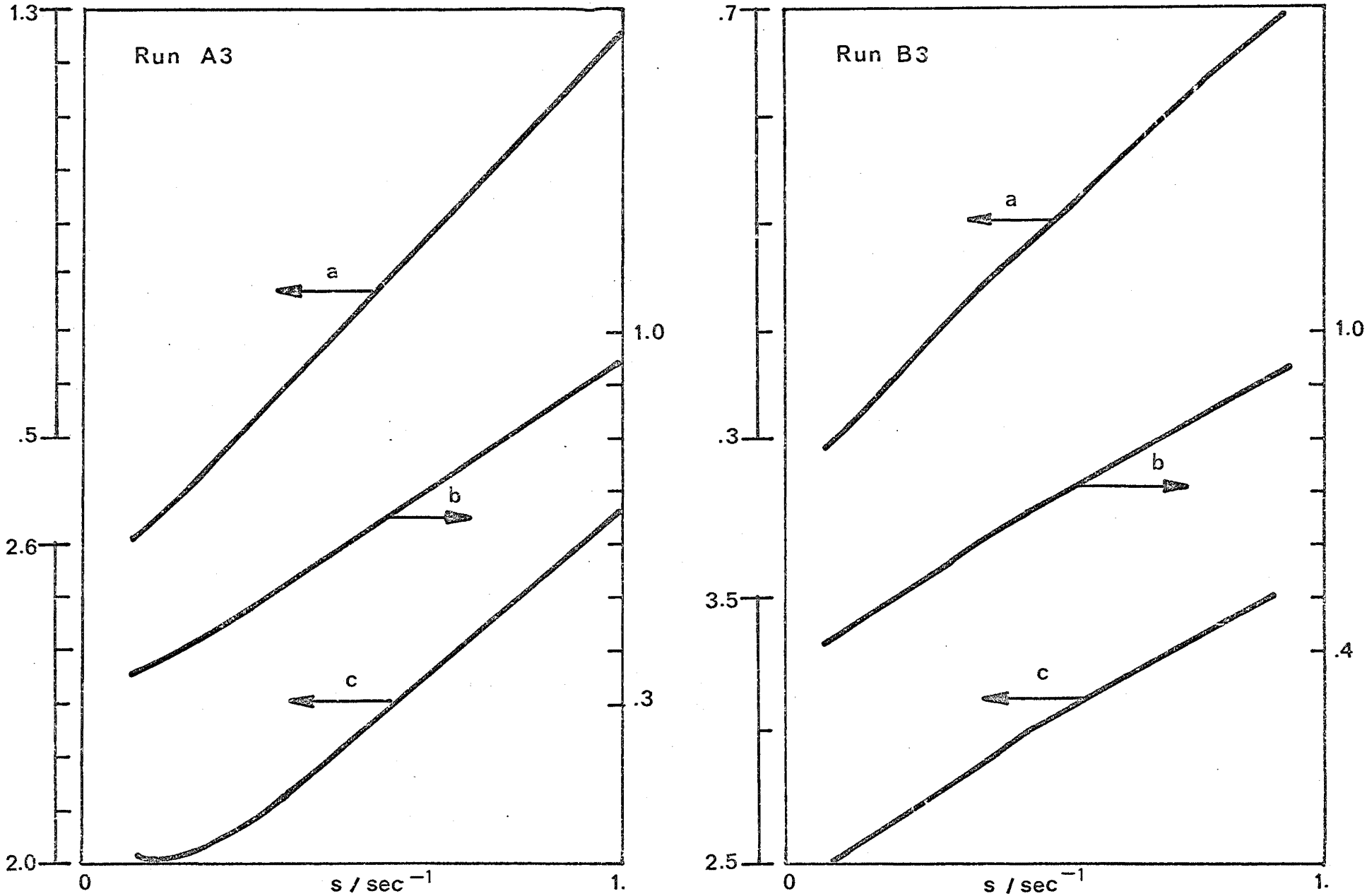


FIGURE 4.5 (cont)

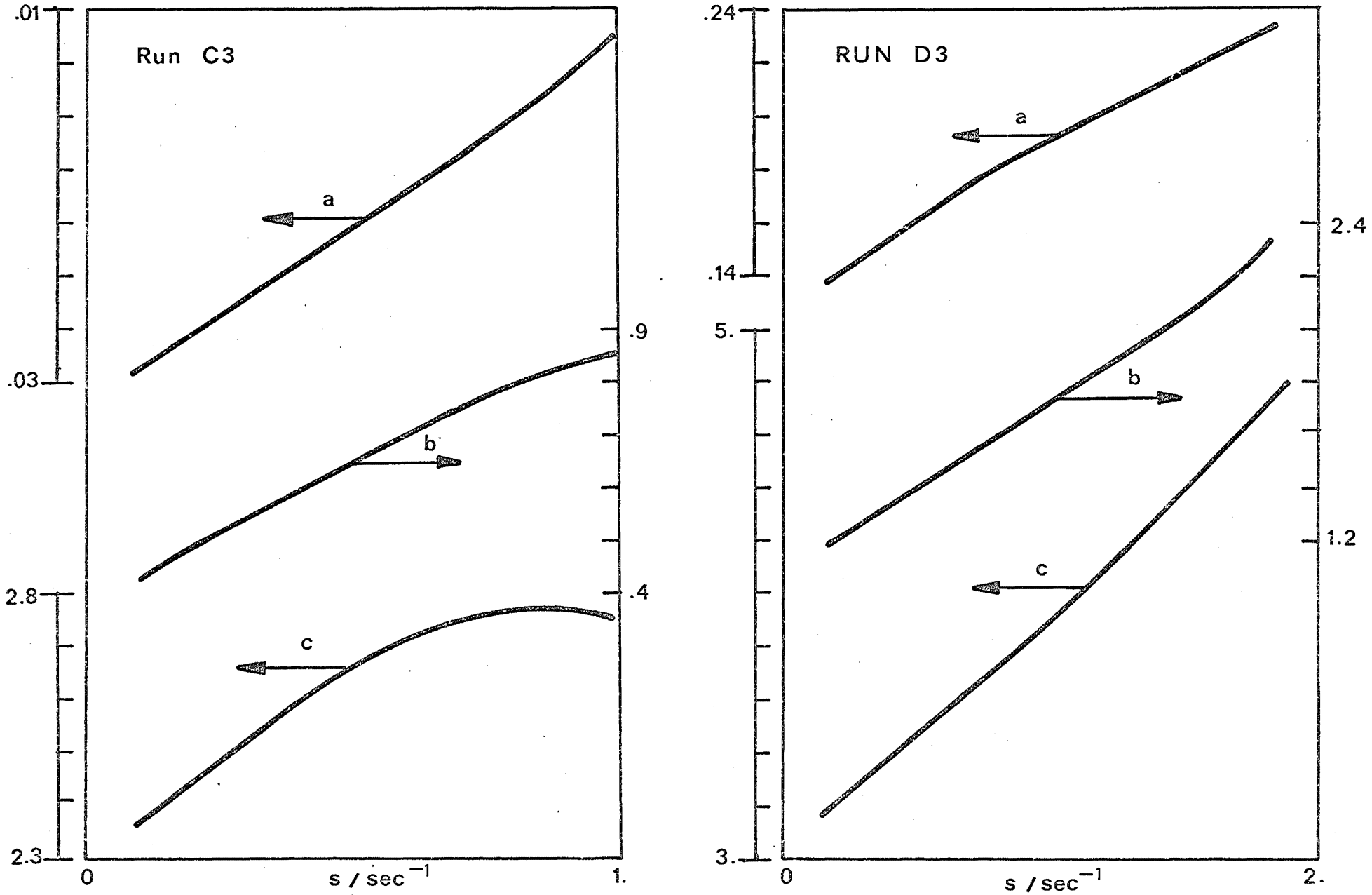


FIGURE 4.5 (cont.)

Curves:

(a) $1/U_1^2$ in sec^{-2}, ADPF model

(b) $1/\sqrt{U_2}$ in sec^{-1}, TSPF model

(c) $U_1/\sqrt{U_2}$ in sec^{-1}, TSPF model

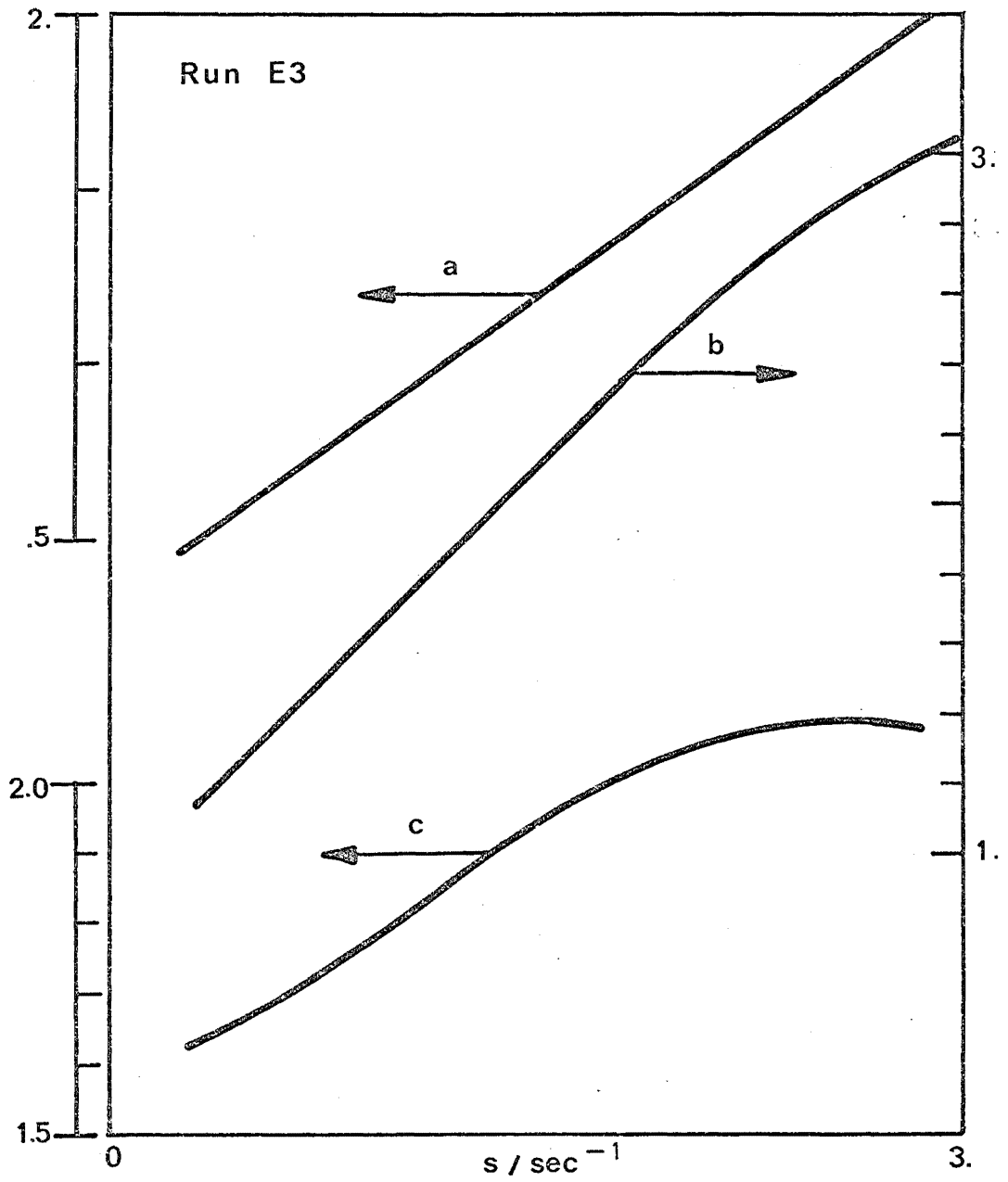


FIGURE 4.5 (cont.)

TABLE 4.4

Transfer function analysis of droplet R.T.D.

Run	A.D.P.F.		T.S.P.F.		
	τ/s	Pe	n	T_t/s	T_p/s
A1	20.5	11.8	3.76	17.4	4.12
A2	14.4	11.3	4.42	11.2	2.7
A3	6.9	5.75	2.15	5.64	1.28
B3	6.36	11.9	2.82	4.32	2.00
C3	6.16	9.65	4.76	5.12	0.75
D3	2.81	21.2	2.14	1.42	1.43
E3	1.74	3.96	2.15	1.32	2.27

IV.3.4 Variation of dispersion with the operating conditions

The interpretation of the Peclet number is complicated by the existence of a size spectrum rather than a single size. Each response curve is thus a superimposition of many possibly different curves, one for each size. Only at very high entrainments will these curves tend to the same.

In run D3 the Peclet number is at a maximum; this occurs at an atomising air date / drying air rate ratio R_u = 0.019, which is near the minimum dispersion point (maximum Pe) for the air flow as well.

IV.3.5 Degree of entrainment

In Table 5 the "predicted" and measured values of the droplet mean residence time, τ_{Dp} and τ_{Dm}, and the atomising air mean residence time, τ_A, are tabulated against the entrainment parameter R_D. The "predicted" values τ_{Dp} were based on the free fall of a particle with diameter D_m with no acceleration or turbulence effect. It can be seen that τ_{Dm} starts to deviate significantly from τ_{Dp} and to tend to τ_A from run C3 onwards, at $R_D \simeq 0.03$. An exception is run D3, where the measured and predicted values τ_{Dm} and τ_{Dp} are much closer than expected. This run is at the minimum dispersion point, where the air-flow pattern and turbulence structure are profoundly altered (Chapter 3), so that R_D may have been overestimated. Also, the droplet flow in this regime may have been confined to a thin core where low turbulence prevails, since it has been found that the air flow is close to the plug flow regime.

TABLE 4.5

Droplet and air mean residence times

Run	R_D	τ_{Dp}/s	τ_{Dm}/s	τ_A/s	$\frac{\tau_{Dm} - \tau_{Dp}}{\tau_A - \tau_{Dp}}$
A1	0	28.3	20.5	31.1	- 1.6
A2	$4.x10^{-5}$	17.5	14.4	29.1	- 0.27
A3	$1.x10^{-3}$	7.4	6.9	29.1	- 0.2
B3	$6.x10^{-3}$	4.24	6.4	14.8	0.2
C3	$2.8x10^{-2}$	4.8	6.2	6.54	0.8
D3	$8.x10^{-2}$	2.63	2.8	3.62	0.2
E3	0.16	1.36	1.74	1.59	1.7

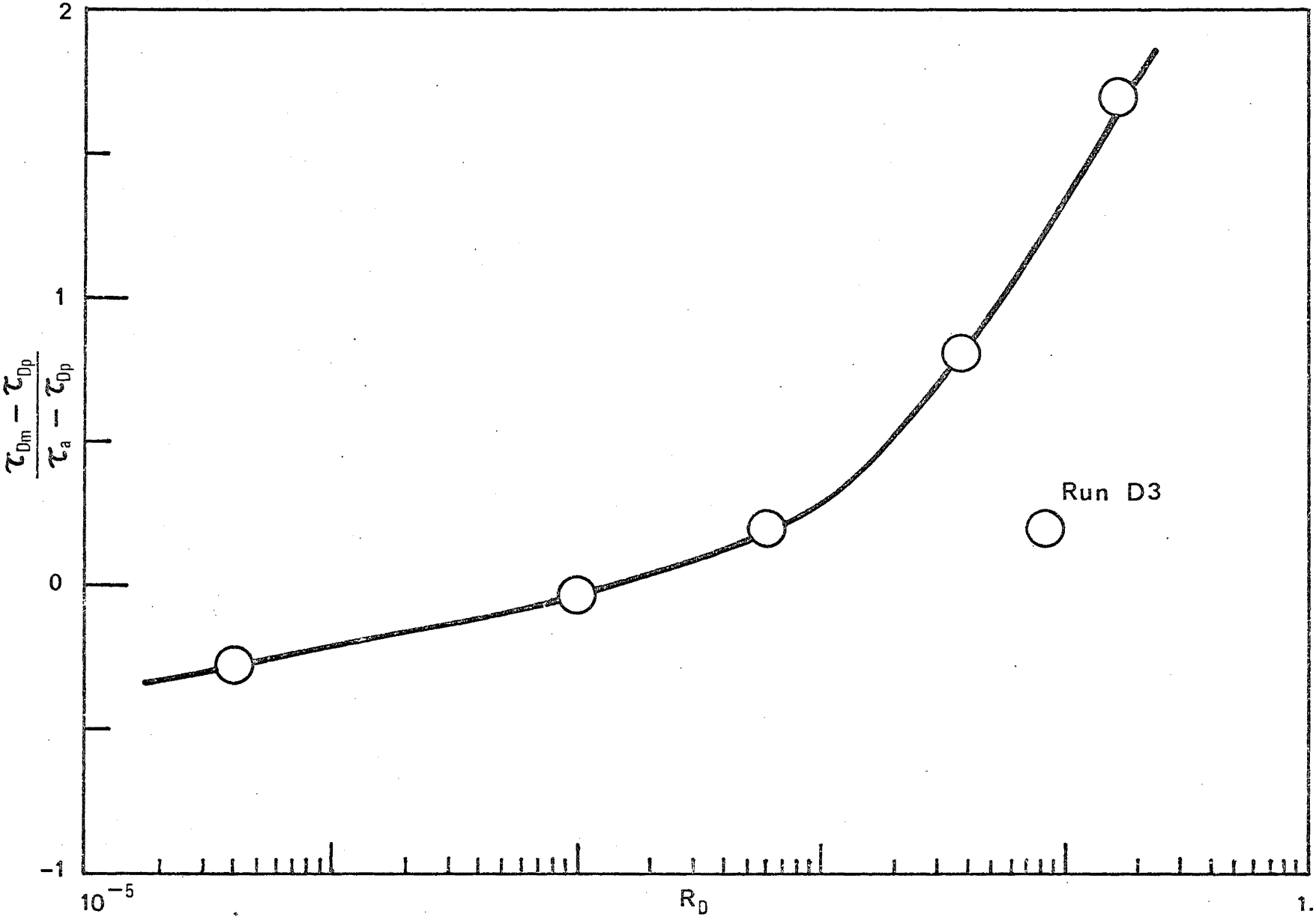


FIGURE 4.6 : EFFECT OF THE ENTRAINMENT PARAMETER R_D

(See errata at front)

A measure of the degree of entrainment is the fractional approach to the air mean residence time R_t:

$$R_t \equiv \frac{\tau_{Dm} - \tau_{Dp}}{\tau_A - \tau_{Dp}} \qquad (4.22)$$

This parameter is tabulated in Table 5 and plotted against R_D in figure 6. It should theoretically range between 0 and 1, but due to the approximations made (replacement of the size spectrum by a single size, neglect of the jet zone and of any bypassing, neglect of the effect of the liquid flow at the nozzle on the atomising air flow pattern), values outside this range are found.

In spite of this, there is a visible correlation between R_D and R_t, except for run D3 at the minimum dispersion point. The R_t curve climbs steeply after $R_D \simeq 5\times10^{-3}$, indicating that turbulence effects, possibly Basset forces, and entrainment become rapidly important from that value onwards.

V. CONCLUSION

On the operation and design of cocurrent spray dryers the following recommendations can be made after examining the results from the present experiment :

(1) It is desirable to promote a high degree of turbulence near the atomiser, in order to disperse the droplets into the air flow and avoid bypassing. For this purpose, a high air inlet velocity may be necessary and can be obtained by forcing the drying air to come in as jets, for example. Alternatively a secondary air stream can be made to impinge on the spray, as in the new Czech-type spray dryers[K9].

(2) When pneumatic or possibly pressure atomisers are used, the

minimum dispersion point (Ct ≃ 0.25, R_u ≃ 0.018) is to be avoided, as bypassing of the whole spray (i.e. insufficient mixing) may occur.

(3) Operating at high air turbulence and entrainment (R_t >> 0.005) increases the drag force and hence should also increase the heat and mass transfer rate, a factor which may improve product quality or at least go some way towards counteracting the adverse effect of backmixing. R_D seems to be a convenient and useful parameter for measuring this effect, but more experimental data would be desirable in order to confirm this.

Quantitatively the results of this experiment are not as rigorous as may be hoped for, and are difficult to interpret because of the existence of a size spectrum. The experiment is of an exploratory nature and many improvements are possible. In particular, the addition of a cascade impactor, such as the one described by May[M9], to the design of the travelling droplet catcher in order to single out a certain size may yield useful results.

NOTATION FOR CHAPTER 4

c_D drag coefficient, [-]

D_m mass-median diameter, [m]

$\mathcal{D}_t$ turbulent diffusivity of fluid, [m^2/s]

$\mathcal{D}_p$ turbulent diffusivity of particles or droplets, [m^2/s]

F_D drag force, [N]

I relative turbulent intensity, $(u'/\bar{u})^2$, [-]

K_L $t_L\, \varepsilon/u'^2$, [-]

n $d(\ell n\, c_D) / d(Re)$, [-]

R_D entrainment parameter, equation 12, [-]

R_t fractional approach of liquid residence time to air residence time, $(\tau_{Dm} - \tau_{Dp}) / (\tau_A - \tau_{Dp})$, [-]

R_u atomising air/drying air flow rate ratio, [-]

s Laplace transform parameter, [s^{-1}]

T_p plug flow time, [s]

T_t total tank time, [s]

t_L Lagrangian time scale of fluid turbulence, [s]

t_{Lp} Lagrangian time scale of particle turbulence, [s]

t_p particle time constant (equation 10), [s]

t_{pt} value of t_p at terminal velocity in quiescent air, [s]

$\bar{u}$ mean air velocity, [m/s]

u' root-mean-square turbulent air velocity, [m/s]

u_p' root-mean-square turbulent particle velocity, [m/s]

$\bar{u}_R$ mean relative velocity, [m/s]

u_R' root-mean=square turbulent relative velocity, [m/s]

u_{Re} effective relative velocity, [m/s]

u_t terminal velocity of particle in quiescent air, [m/s]

U_o, U_1, U_2 functions of the transfer function as defined in Chapter 2.

(Notation for Chapter 4, cont.)

ε turbulent energy dissipation per unit mass, [m^2/s^3]

ν fluid kinematic viscosity, [m^2/s]

λ_g Eulerian lateral microscale of turbulence, [m]

λ_L Lagrangian microscale of turbulence, [m]

τ mean residence time, or parameter in the A.D.P.F. model, [s]

τ_A atomising air mean residence time, [s]

τ_{Dm} measured droplet mean residence time, [s]

τ_{Dp} predicted droplet mean residence time based on zero turbulence, [s]

Dimensionless numbers

Ct Craya-Curtet number = (vessel radius x drying air velocity)/ (nozzle radius x atomising air velocity)

Pe Peclet number for A.D.P.F. model

Re (particle) Reynolds number

CHAPTER 5

TRANSPORT PHENOMENA FOR SINGLE DROPLETS

Chapter contents:

INTRODUCTION

A detailed knowledge of transfer phenomena to single droplets is a starting point to any study of spray evaporation. Extensive reviews have been done elsewhere on this subject (M6,M8,S3,B17,F8) and we shall not attempt to repeat them, but simply to summarise the most significant results to serve as a basis for the next chapter. Some aspects, however, have not received much attention before and will be dealt with in more detail.

I. BASIC EQUATIONS OF TRANSFER

I.1 Mass and heat transfer

For a spherical body in an infinite quiescent fluid it can be shown analytically that (L1):

$$Nu = 2 \tag{5.1a}$$

$$Sh = 2 \quad . \tag{5.1b}$$

When the particle and the fluid are in relative motion, it can be expected from dimensional analysis that:

$$Nu = Nu\ (Re, Pr) \tag{5.2a}$$

$$Sh = Sh\ (Re, Sc) \tag{5.2b}$$

and much work has been done to determine the actual form of these equations. (A5,F7,E1,G2,H22,J2,M1,P4,P12,R3,R4,W3) The most widely accepted form is that due to Frössling (F7):

$$Nu = 2 + \beta\ Re^{\frac{1}{2}}\ Pr^{1/3} \tag{5.3a}$$

$$Sh = 2 + \beta\ Re^{\frac{1}{2}}\ Sc^{1/3} \quad . \tag{5.3b}$$

Values of β found experimentally range from 0.52 to 0.72 (B16, P12) except for a value of 0.95 found by Garner and Suckling (G4) for solid spheres in liquids. The most widely quoted value, and the one used

in this work because of its intermediate value and the close resemblance between the experimental condition and the spray drying situation (droplets in air), is that due to Ranz and Marshall[R4]:

$$\beta = 0.6 \ . \tag{5.3b}$$

These authors also pointed out that in evaluating the dimensionless numbers, the average film properties (at a temperature and concentration equal to the arithmetic mean between the surface and bulk fluid values) should be used. Some care must be exercised in defining Nu when the mass transfer has an important effect on the heat transfer. Equations 3a and 3b can be rewritten in terms of the heat transfer rate q and mass transfer rate $\dot{m}$ as:

$$q = \pi \, k_f \, D_p \, (T_\infty - T_s) \, (2 + 0.6 \, Re^{\frac{1}{2}} \, Pr^{1/3}) \tag{5.4a}$$

$$\dot{m} = \pi \, \mathfrak{D}_{AB} \, D_p \left(\frac{c_{A\infty} - c_{As}}{x_{BM}}\right) (2 + 0.6 \, Re^{\frac{1}{2}} \, Sc^{1/3}) \tag{5.4b}$$

where D_p is the particle diameter, k_f the gas thermal conductivity, $\mathfrak{D}_{AB}$ the diffusion coefficient, T_∞ and T_s the fluid and surface temperatures, $c_{A\infty}$ and c_{As} the fluid and surface (mass-) concentration of the transferred substance, and x_{BM} the log-mean mole fraction of the non-transferred substances between infinity and surface. At steady state, equations 4a and 4b are coupled by the heat balance:

$$q = - \lambda \, \dot{m} \tag{5.5}$$

and the equilibrium curve:

$$c_{As} = c^*_{As}(T_s) \tag{5.6}$$

so that the system of equations (4a, 4b, 5, 6) can be solved for q, $\dot{m}$, T_s and c_{As} when the other variables are known.

For the water-air system

$$Pr \simeq Sc \tag{5.7}$$

or

$$\frac{k_f}{\mathcal{D}_{AB} c_{pf} \rho_f} \simeq 1 \tag{5.8}$$

where c_{pf} and ρ_f are the specific heat and density of the fluid, hence equations 4a and 4b can be reduced to:

$$\frac{T_\infty - T_s}{y_\infty - y_s} \simeq - \frac{\lambda}{c_{pf}} = \frac{T_\infty - T_s^*}{y_\infty - y_s^*} \tag{5.9}$$

that is, the surface temperature and humidity ($y_s = c_{As}/(\rho_f - c_{As})$) are equal to the adiabatic saturation temperature T_s^* and humidity y_s^* respectively, and independent of Re. Equations 4a, 4b and 5 can now be reduced to:

$$\dot{m} = - \frac{\pi k_f D_p (T_\infty - T_s^*)}{\lambda} (2 + 0.6 \, Re^{1/2} \, Pr^{1/3}) \tag{5.10}$$

(one equation in one unknown, $\dot{m}$) .

If the particle is a spherical droplet of pure liquid, the rate of shrinking can be easily derived from equation 10:

$$\frac{d(D_p^2)}{dt} = - \frac{4 k_f (T_\infty - T_s^*)}{\rho_p \lambda} (2 + 0.6 \, Re^{1/2} \, Nu^{1/3}) \quad . \tag{5.11}$$

For the quiescent-fluid case (equation 1) this reduces to:

$$\frac{d \, D_p}{dt} = - \frac{4 \, k_f (T_\infty - T_s^*)}{\rho_p \lambda} \frac{1}{D_p} \tag{5.12a}$$

or

$$\frac{d(D_p^2)}{dt} = \text{constant} \tag{5.12b}$$

an equation extensively used in the spray drying literature.

Finally, if one puts E = fractional evaporation, equation 10 becomes:

$$\frac{dE}{dt} = \frac{\pi k_f D_p (T_\infty - T_s^*)}{\lambda m_o} \left(2 + 0.6 \, Re^{1/2} Pr^{1/3} \right) \qquad (5.13)$$

for a pure water droplet, where m_o is the initial droplet mass. If the droplet contains solids

$$\frac{dE}{dt} = \frac{\pi k_f D_p (T_\infty - T_s^*)}{\lambda m_o w_{\ell o}} \left(2 + 0.6 \, Re^{1/2} \, Pr^{1/3} \right) \qquad (5.13a)$$

where $w_{\ell o}$ is the initial solid mass fraction.

I.2 Momentum transfer

The drag coefficient

$$c_D = \frac{\text{drag force}}{\text{inertial stress x projected area}} \qquad (5.14)$$

has been plotted for solid spherical particles by Lapple and Shepherd[L2]. This "standard drag curve" has won universal acceptance and still serves as a basis for subsequent modifications due to deformation, deviations from sphericity, turbulence and other effects[T5, T6].

For low Reynolds numbers (Re < .1) the flow around a sphere is laminar and c_D is given by Stokes's equation:

$$c_D = \frac{24}{Re} \quad . \qquad (5.15)$$

For higher Reynolds numbers, many equations have been proposed, both theoretical[H2,H3, H8, K2] and empirical[B6,C5,D5,G4,H6,I1,K1,S3, S12,U1]. Apart from Ingebo[I1], most of the latter are simply attempts to approximate the standard drag curve by algebraic equations. After investigating several of these, the author found that the following

segmentwise approximation gives the best fit (± 4% up to Re = 5000) :

$$c_D = 24/Re \qquad Re \leq .4 \tag{5.16a}$$

$$= \frac{24}{Re}(1 + 0.1\ Re), \quad .4 < Re \leq 2. \tag{5.16b}$$

$$= \frac{24}{Re}(1 + 0.15\ Re^{.687}) + \frac{0.42}{1 + 4.25\times10^{4} Re^{-1.16}} \tag{5.16c}$$

$$2 < Re \leq 5000$$

The second equation is similar to Oseen's equation (O.2), the third is Schiller and Naumann's equation (S2) with an extra term by Clift and Gauvin (C5).

Lapple and Shepherd (L2) have also derived general equations for the motion of particles in several cases of interest, while Sjetnitzer (S11) considered cases where the particles are shrinking during motion.

In many cases, the droplet or particle will travel at its terminal velocity u_t with respect to the gas. If Stokes's equation applies, then u_t is given by:

$$u_t = \frac{D_p^{\,2}(\rho_p - \rho_f)\ g}{18\ \mu_f} \tag{5.17}$$

where g is the acceleration of gravity and μ_f the fluid viscosity. Outside the laminar regime u_t is usually computed numerically (P6). However, Smith (S12, B17) has derived the following equation which can be used for u_t :

$$c_D = \frac{576}{\Pi} + \frac{32}{\Pi^{.39}} + \frac{1}{1.8 + 758\ \Pi^{-.36}} \tag{5.18}$$

where $\Pi = c_D Re^2$

$$\Pi = \Pi_t = \frac{4\, g\, \rho_f\, D_p^{\,3} (\rho_p - \rho_f)}{3\, \mu_f^{\,2}} \qquad (5.19)$$

at the terminal velocity [P6]. This equation has been found by the author to apply in the range $\Pi > 10$. For $\Pi \leq 10$, equation 17 can be used (Table 1).

Π_t is a measure of the relative importance of the gravitational and drag forces acting on a particle at settling velocity. It has been found [D7, H14] that water droplets with diameters less than about 40 μm will follow the motion of the surrounding air stream. In terms of Π_t the condition for complete entrainment can thus be stated:

$$\Pi_t < 4 \qquad (5.20)$$

TABLE 5.1

Terminal coefficients by Stokes's and Smith's equations

Re	$\Pi = c_D R_e^{\,2}$		c_D	
		Experiment	Stokes	Smith
.1	2.4	240.	240.	
.3	7.2	80.	80.	
.7	17.9	36.5	32.1	42.5
2	57.6	16.6	10.0	16.6
10	410.	4.1		4.5
200	3.1×10^4	.77		.64
1000	4.6×10^5	.46		.31
3000	3.6×10^6	.40		.28
7000	1.9×10^7	.39		.32
20000	1.8×10^8	.45		.40

II. VARIOUS INFLUENCES ON PARTICLE-FLUID TRANSFER PHENOMENA

II.1 Effect of mass flux on heat transfer

In simultaneous heat and mass transfer, some heat is transported by convection as well as conduction, the transferred matter taking up or releasing some of the heat as it goes through a thermal gradient. In this case, care must be exercised in defining the heat transfer coefficients h and the Nusselt number $Nu = h\, D_p/k_f$.

The commonest practice is to define h and Nu as "apparent" transfer coefficients:

$$h \equiv \frac{q_s}{T_\infty - T_s} \tag{5.21}$$

where q_s is the heat transferred to the particle surface. The total heat lost (gained) by the surroundings will be greater (less), due to heat being used in heating (cooling) the evaporating (condensing) vapour. Thus defined, h and Nu differ from the "true" or zero-mass-flux values h_o, Nu_o by a factor

$$f_{Nu} \equiv \frac{Nu}{Nu_o} = \frac{h}{h_o} \quad .$$

When mass is being transferred from the particle to its surroundings, f_{Nu} will always be less than 1. The governing parameter here is Spalding's number:

$$B \equiv \frac{c_{pv}(T_\infty - T_s)}{\lambda} \quad . \tag{5.22}$$

Several relationships have been proposed, among them:

(a) The film theory[S16, R4]:

$$f_{Nu} = \frac{\ell n\ (1+B)}{B} \tag{5.23}$$

(b) The laminar boundary layer theory [E2]:

$$f_{Nu} = \frac{1}{1+B} \tag{5.24}$$

(c) The slow-viscous flow theory [E2]:

$$f_{Nu} = (1 + B/2)^{-1} \tag{5.25}$$

(d) Hoffmann and Ross's boundary layer theory [H17]:

$$f_{Nu} = (1 + B)^{-.6} \tag{5.26}$$

A comparison of the predictions of these equations for the water air system is shown in Table 2. Equation 24 seems to be the most widely accepted in spray drying situations [K3].

TABLE 5.2

Predictions of mass flux effect on heat transfer for air-water systems.

$\Delta T/K$	50	100	150	200
$1 - B$	.021	.042	.063	.085
$1 - \ell n(1+B)/B$	.011	.021	.032	.041
$1 - (1+B)^{-1}$	.021	.040	.059	.079
$1 - (1+B/2)^{-1}$	.010	.021	.040	.059
$1 - (1+B)^{-.6}$	.013	.024	.036	.048

II.2 Effect of free convection

Free convection adds another component to the relative velocity. Fuchs [F8] proposed that in Ranz and Marshall's equation 3, Re should be replaced by $Re = \sqrt{Gr}$.

II.3 Effect of Radiation

(a) Particle in a dilute cloud:

A single particle at temperature T_p in an infinitely large vessel with wall temperature T_w will receive a radiant heat rate:

$$q_R = \sigma \pi D_p^2 \alpha_p (T_w^4 - T_p^4) \qquad (5.27)$$

where α_p is the particle absorptivity and σ is Stefan-Boltzmann's constant. For liquid droplets the prediction of α_p is very difficult. Multiple reflections, refractions and absorptions inside the droplet must be considered [H21]. If the droplet contains solids as well, the problem becomes intractable, and α_p must be determined experimentally. A discussion of the importance of radiation in spray drying can be found in reference H15.

When gas radiation is also important, equation 27 can no longer be used because of interaction between wall, gas and particles, each of which emits and transmits or reflects radiation simultaneously. According to Hottel and Sarofim [H21], we can define a net leaving flux or radiosity density W, which is the sum of transmitted, reflected and emitted radiant energy per unit solid angle (steradian) at each point. The manner in which W can be calculated for any system has been described by Hottel and Sarofim [H21] and applied to spray drying chambers by Hoffmann and Gauvin [H15, H16]. Briefly, it consists of subdividing the system into elements of surface and volume

which are assumed to be at uniform temperatures. The radiant transfer to a particle is then given by

$$q_R = \pi D_p^2 \frac{\alpha_p}{1-\alpha_p} (W - \sigma T_p^4) \tag{5.28}$$

(b) Particle in a dense cloud

For particles in a dense cloud gas radiation may not be important because of the short mean beam length between particles. On the other hand, particles now tend to shield each other from the wall, so that a wall-particle view factor S_{wp} must be introduced into equation 27:

$$q_R = \sigma \pi D_p^2 \alpha_p S_{wp} (T_w^4 - T_p^4) \tag{5.29}$$

S_{wp} takes into account directly-received as well as reflected radiation. The rest of this section will be devoted to the calculation of this factor S_{wp}, which has received little attention so far. We first consider the cloud absorptivity α_c, which is the fraction of light impinging on the cloud absorbed by it. α_c has been related to α_p by:[P6]

$$\alpha_c = 1 - \exp(K_e L_b \alpha_p) \tag{5.30}$$

where K_e is the "extinction coefficient" of the cloud, or projected particle area ($\pi D_p^2/4$ per particle) per unit cloud volume, and L_b is the mean beam length, defined as the length of a parallel beam after which the same fraction of the original light has been intercepted as in the actual situation. For $\alpha_p < 1$ this equation is in error, as it implies that reflected light continues to travel in the same direction as before. We shall therefore try to derive a more accurate expression.

Consider a beam of light of intensity I_o falling on the cloud (Figure 1). For each increment of distance dx a fraction $K_e dx$ of the light is intercepted, hence the intensity I of the beam is

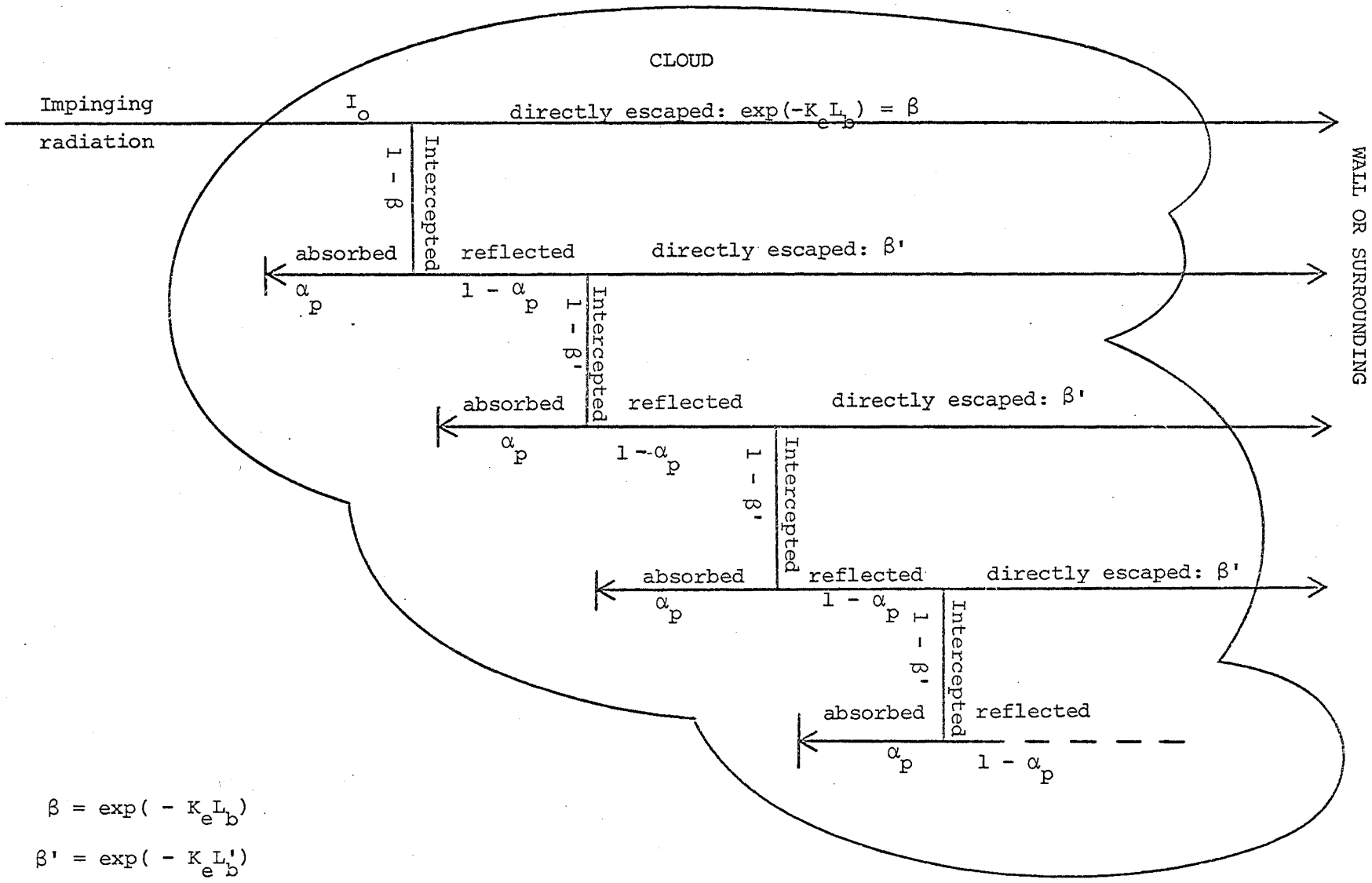


FIGURE 5.1: MULTIPLE REFLECTIONS & ABSORPTIONS IN A CLOUD

decreasing at a rate:

$$\frac{dI}{I} = K_e dx \quad . \tag{5.31}$$

Hence, by integrating (31) from 0 to L_b :

$$\text{Unintercepted light} = I_o \exp(- K_e L_b) \tag{5.32}$$

$$\text{First-time intercepted light} = I_o \ (1 - \exp(K_e L_b) \ ) \tag{5.33}$$

Of the first-time intercepted light, a fraction α_p is absorbed and $(1 - \alpha_p)$ is reflected:

$$\text{First absorption} = I_o \ \{1-\exp(K_e L_b)\}\alpha_p \tag{5.34}$$

$$\text{First reflection} = I_o \ \{1-\exp(K_e L_b)\} \ (1-\alpha_p) \tag{5.35}$$

The light from the first reflection travels another mean beam length L_b' ($\neq L_b$) before reaching the cloud boundary. Along similar lines of reasoning it can be seen that:

$$\text{Second-time intercepted light} = \text{1st reflection} \times (1-\exp(K_e L_b'))$$

$$= I_o\{1-\exp(-K_e L_b)\} \ (1-\alpha_p) \ \{1-\exp(-K_e L_b')\} \tag{5.36}$$

$$\text{Second-time absorbed light} = \text{2nd time intercepted light} \times \alpha_p$$

$$= I_o\{1-\exp(-K_e L_b)\} \ (1-\alpha_p) \ \{1-\exp(-K_e L_b')\}\alpha_p \tag{5.37}$$

By comparing equations 37 and 34 we see that the ratio between successive absorptions is:

$$r = (1-\alpha_p) \ \{1-\exp(-K_e L_b')\} \quad , \tag{5.38}$$

and we can assume this ratio to remain constant since after the second, third ... reflections the mean beam length for the reflected light to travel before it reaches the cloud boundary remains constant at L_b' .

To find the total absorption, we sum up the successive absorptions (which form a geometric series):

$$\text{Total absorption} = \text{1st absorption} \times \sum_{j=o}^{\infty} r^j$$

$$= I_o \frac{\alpha_p (1-\exp(-K_e L_b))}{1 - (1-\alpha_p)(1-\exp(-K_e L_b'))} \tag{5.39}$$

Since α_c is the fraction of I_o which is absorbed,

$$\alpha_c = \frac{\alpha_c (1-\exp(-K_e L_b))}{1-(1-\alpha_p)(1-\exp(-K_e L_b'))} \quad . \tag{5.40}$$

Now the mean beam length from boundary to boundary L_b is twice the mean beam length from boundary to particle L_b' :

$$L_b = 2L_b' \tag{5.41}$$

hence equation 40 becomes:

$$\alpha_c = \frac{\alpha_p \{1-\exp(-K_e L_b)\}}{1-(1-\alpha_p)\{1-\exp(-K_e L_b/2)\}} \quad . \tag{5.42}$$

Equation 42 enables the wall-to-cloud radiation transfer $q_{w \to c}$ to be calculated by the standard equation[H21]:

$$q_{w \to c} = \frac{\sigma A_c}{1/\alpha_c + 1/\alpha_w - 1} \quad (T_w^4 - T_p^4) \tag{5.43}$$

where A_c is the cloud outside area which is also the wall area of the chamber and α_w is the chamber wall emissivity.

We now put

$$q_{w \to c} = q_R \quad V_c \; n \tag{5.44}$$

where q_R is the radiation to one particle, V_c the cloud or vessel volume, n the number of particles per unit cloud volume. Substituting equations 43 and 29 into 44, we get:

$$S_{wp} = \frac{A_c}{(1/\alpha_c + 1/\alpha_w - 1)\; V_c \; n \; \pi D_p^2 \alpha_p} \quad . \tag{5.45}$$

But $A_c/V_c \equiv 4D_h$ where D_h is the hydraulic diameter of the cloud or vessel, and $n\pi D_p^2 \equiv 4K_e$, hence equation 45 becomes:

$$S_{wp} = \left[\alpha_p (K_e D_h)\ (1/\alpha_c + 1/\alpha_w - 1)\right]^{-1} \qquad (5.46)$$

where α_c is given by equation 42.

There now remains to estimate the mean beam length L_b in equation 42. In gas radiation L_b is defined by:

(5.47)

Absorption through $L_b \simeq$ Absorption by given volume and shape of gas.

Hottel (H20) showed that for this approximate equation to hold to a few per cent it is sufficient to take $L_b \simeq 0.9\ D_h$. But in our case, due to the presence of reflections, this approximate definition may lead to error. So we define L_b by the exact form of equation 47, which can be written as: (H20)

$$\exp(-K_e L_b) = \frac{2\pi\int \exp(-K_e x) \quad \text{(View angle factor) d (solid angle)}}{\int_{2\pi} \text{(view angle factor) d (solid angle)}} \qquad (5.47b)$$

where x is the boundary-to-boundary distance in a certain direction. Ways of determining these integrals are described in reference H21. The only case in which equation 47 can be expressed analytically is that of a spherical cloud (chamber):

$$K_e L_b = -\ln\left\{\frac{8}{9(K_e D_h)^2}\left[1 - (1 + \frac{3}{2} K_e D_h)\exp(-\frac{3}{2} K_e D_h)\right]\right\} \qquad (5.48)$$

However, numerical integration of equation 47 shows that $K_e L_b$ varies with $K_e D_h$ in almost exactly the same ways for infinite cylinders (Table 3). Hence equation 48 can be used for both, and also for any intermediate geometry.

TABLE 5.3

Mean beam lengths of spheres and infinite cylinders

$K_e D_h$	$K_e L_b$	
	sphere	cylinder
0.2	.198	.195
1.	.93	.91
3.	2.4	2.3
5.	3.4	3.4
10.	4.7	4.8
100.	9.3	9.4

Note:

D_h = cylinder diameter

$= \frac{2}{3}$ x sphere diameter

TABLE 5.4

Wall-particle view factor predictions

α_p	$K_e D_h$	S_{wp}	
		present method	equation 30
.1	1.	.91	.86
	2.	.85	.82
	5.	.72	.72
	10.	.53	.59
.5	1.	.74	.72
	2.	.58	.59
	5.	.33	.36
.8	1.	.65	.64
	2.	.46	.48
	5.	.23	.24

To sum up our results so far: we use equation 48 to calculate L_b, equation 42 to calculate α_c, equation 46 to calculate S_{wp}, and equation 29 to evaluate the wall-to-particle radiation.

When $K_e D_h \to 0$ (very dilute cloud),

$K_e L_b \to K_e D_h$ (from eqn.48)

$\alpha_c \to \alpha_p K_e D_h$ (from eqn 42)

$S_{wp} \to 1$ (from eqn. 46), as expected.

Exactly the same result applies when $\alpha_p \to 0$, which means that if the particles are highly reflecting, the multiple reflections compensate for the intercepted light.

Table 4 gives some values of S_{wp} as calculated by the present method (equations 48, 42, 46, 29) and also by a combination of eqns.30 and 46 (in eqn.30 we use $L_b = 0.9\ D_h$ as recommended in the literature). As expected, when α_p is small and $K_e D_h$ not large, equation 30 leads to a low value of S_{wp} because it fails to take multiple reflections into account, while when $K_e D_h$ is large, it predicts a high S_{wp} because it overestimates the mean beam length and neglects the light bouncing off the cloud at an early stage. However, in most cases the errors are not large and unless a great accuracy is required equation 30 would be adequate.

The equations derived for α_c can also be quite useful in estimating the radiosity W in dense cloud situations, whence an accurate calculation of the wall-to-particle radiation is facilitated (equation 28), even when the wall temperature is not uniform as assumed in equation 29.

II.4 Influence of turbulence

The effect of turbulence on transfer phenomena in particle-fluid systems has been the subject of a vast amount of works. Several approaches have been tried and results are often contradictory.

In the field of momentum transfer, theoretical (B1,F6,L8,S14,S15) as well as experimental (K14,B1,L9,T6) studies are numerous. Some of the latter show that the drag force is increased by turbulence (U1), while others show a decrease (T6, C5), and some find no effect (B17). Theoretical analysis, on the other hand, shows that the drag can be either increased or decreased depending on the pattern of turbulence, although an increase is the more common case. All theoretical works point to the important influence of scales of turbulence, while many experimental investigations either found no scale effects or simply ignore them.

A similar situation exists in the field of mass and heat transfer. Here again theoretical analysis points to a turbulence-scale effect (K13,L8). While some experimental studies demonstrate this (G7, H7, K13, R3), others show that turbulence intensity is the only factor (G2, L3, M2), and some do not find any effect at all (D7, B15). The lack of a unified approach to the correlation of results poses a handicap to an attempt to compare them: while some workers present the turbulence effect as empirical factors to be inserted into the transfer equations (eq.2) (G2, G7, H7), others keep these equations unchanged, but introduce extra components in the Reynolds number, attributed to turbulence (L8,K13).

Many of the experimental works have been done on large, fixed spheres, hence the results may not be directly applicable to spray-drying situations. Studies on the separation of the boundary layer and the interaction of turbulence with the wake suffer particularly

in this respect. Torobin and Gauvin [T6] did extensive work on free-falling spheres, but these are fairly large (1.5 mm - 3 mm). The main effect they found was the earlier occurrence of the critical Reynolds number Re_c, at which the drag coefficient c_D suddenly falls off to below 0.3 . In turbulent flow Re_c occurs at 500-5000 (instead of 4×10^5 for the standard drag curve) for $u_f'/u_R = 0.1$ to 0.4, where u_f' is the turbulent component of the fluid velocity. In spray drying, particle sizes are usually below 300 μm for which Π (as defined in equation 19) is $\simeq$ 1000 and Re $\simeq$ 20 at the terminal velocity, hence this effect will not be important.

Comprehensive reviews of turbulence effects can be found in reference B17, T5, G2, F9. In the absence of definitive results, the theoretical approach of Friedlander [F6] and Levins and Glastonbury [L8] will be followed: first, evaluate the momentum transfer and relative turbulent velocities, then use them as a basis for calculating the added mass and heat transfer, according to standard relationships. This approach is deemed suitable for the low Reynolds number and small particle sizes encountered in spray-drying practice.

II.4.1 Effect of turbulence on momentum transfer:

(a) Force balance on the particle:

Most theoretical studies of particle motion in turbulent fields start from Tchen's equation [S15] which states that:

$$\text{Net force on particle} = \text{Drag} + \text{Pressure gradient effect} + \text{added mass effect} + \text{Basset force} + \text{Body force} \qquad (5.49)$$

As Bailey [B1] pointed out, the effect of turbulence is mainly due to changes in the first and fourth terms of the right-hand side.

Added mass effects can be neglected in solid-gas systems. The Basset force constitutes a resistance to the unsteady state of the flow field. It can be neglected if

$$D_p\sqrt{\frac{\pi\rho_f}{2\mu_f\tau}} < 1 \tag{5.50}$$

where τ is the period of the oscillation. For large particles at high energy dissipation (low τ) this term can be quite large, especially when the fluid is a liquid, but it must usually be determined experimentally.

The effect of turbulence on the first term (drag force) can be easily explained qualitatively. Since

$$F_D = a\,Re^b \tag{5.51}$$

where $b > 1$ (except in Stokes's regime) and F_D is the drag force, if Re is oscillating about a mean value $\overline{Re}$, we have:

$$\overline{F}_D = \overline{(aRe^b)} > a\overline{Re}^b \tag{5.52}$$

hence the mean drag force is increased with respect to the steady-state case. Quantitatively the effect is more difficult to calculate. The author suggests a vectorial addition of the average and turbulent components of velocity in calculating c_D and F_D :

$$Re_e = \sqrt{\bar{u}_R^{\,2} + u_R'^{\,2}} \tag{5.53}$$

$$c_D = c_D(Re_e)$$

$$F_{Di} = \frac{1}{2}\,c_D\,\frac{\pi D_p^{\,2}}{4}\left(\sqrt{\bar{u}_R^{\,2} + u_R'^{\,2}}\right)\overline{u_{Ri}} \tag{5.54}$$

where $\bar{u}_R$ is the mean relative velocity, u_R' the root-mean-square turbulent relative velocity and i refers to the i-th direction.

(b) Effect of turbulence on relative motion:

Ignoring all terms on the right of equation 49 except the drag force, we have:

$$\rho_p \cdot \frac{\pi D_p^3}{6} \cdot \frac{du_R}{dt} = -\frac{1}{2} \cdot \frac{\pi D_p^2}{4} \cdot c_D \rho_f |u_R| u_R \qquad (5.55)$$

or

$$\frac{du_R}{dt} = -\frac{u_R}{t_p} \qquad (5.56)$$

where t_p is the particle time constant:

$$t_p = \frac{4 \rho_p D_p}{3 \rho_f c_D |u_R|} \qquad (5.57)$$

For Stokes's regime, this becomes:

$$t_p = \frac{\rho_p D_p^2}{18 \mu_f} \qquad (5.58)$$

t_p is the ratio of the inertia of the particle to the drag force acting on it, and is a measure of how fast it can respond to velocity fluctuations in the fluid.

In Stokes's regime, Friedlander showed that

$$\frac{u_R'^2}{u_f'^2} = \frac{1}{1 + t_L/t_p} \qquad (5.59)$$

where u' is the rms turbulent fluid velocity and t_L the Lagrangian time scale of turbulence. We shall assume that this result also holds in the turbulent regime, with t_p given by equation 57.

II.4.2 Effect of Turbulence on heat and mass transfer

In a turbulent field, heat and mass transfers are enhanced by two effects: the turbulent relative velocity u'_R and the turbulent velocity gradient.(L8) The latter has been found to be important in stirred vessel, especially at high energy dissipation rate, but it has not been correlated for gas-solids systems. Levins and Glastonbury suggest that in calculating the effective Reynolds number, the turbulent and average components of velocity should be added vectorially (equation 53). Then Nu and Sh can be calculated by standard relationships.

II.5 Effect of droplet sensible heat

When the droplet is not at the equilibrium surface temperature, some heat goes to heating or cooling it, so that the heat balance (equation 5) becomes:

$$q = - \lambda \dot{m} + c_{pp}\, m \frac{dT_p}{dt} \qquad (5.60)$$

where c_{pp} is the particle specific heat, m its mass, and T_p its mean temperature. Usually the sensible heat term has a magnitude nearly two orders below that of the heat of evaporation term (K4) and can be ignored.

One case when the sensible heat is important is near the atomiser orifice, when the droplets are still essentially at the feed temperature which can be substantially higher than adiabatic saturation point (this is usually done purposely to accelerate the evaporation). The transfer equations 4a, 4b now become:

$$q' = \pi k_f D_p (T_\infty - T_p)\ (2 + 0.6\ Re^{1/2}\ Pr^{1/3}) \qquad (5.61)$$

$$\dot{m}' = - \pi \mathfrak{D}_{AB} D_p \frac{c^*_{Ap} - c_{A\infty}}{x'_{BM}} (2 + 0.6 \, Re^{1/2} \, Sc^{1/3}) \tag{5.62}$$

where c^*_{Ap} is the vapour mass concentration in equilibrium with T_p and the dash refers to non-steady state ($T_p \neq T^*_s$) conditions.

In computations it will be convenient to express $q', \dot{m}'$ in terms of the steady-state values q , $\dot{m}$, when the droplet is at adiabatic saturation conditions T^*_s , c^*_{As} (or T^*_s , y^*_s). For this we introduce the correction factors S_m , S_h :

$$S_m \equiv \frac{\dot{m}'}{m} = \frac{c^*_{Ap} - c_{A\infty}}{c^*_{As} - c_{A\infty}} \cdot \frac{x_{BM}}{x'_{BM}} \tag{5.63}$$

$$S_h \equiv \frac{q'}{q} = \frac{T_\infty - T_p}{T_\infty - T_s} \tag{5.64}$$

The rate of decrease of the droplet temperature can be obtained from equations 60, 63 and 64 :

$$\frac{dT_p}{dt} = \frac{S_q q + \lambda S_m \dot{m}}{c_{pp} m} \tag{5.65}$$

q and $\dot{m}$ are the (hypothetical) steady-state transfer rates (for $T_p = T^*_s$). But

$$\lambda \dot{m} = - q \tag{5.5}$$

hence

$$\frac{dT_p}{dt} = \left(\frac{S_q - S_m}{c_{pp} m} \right) q = \left(\frac{S_m - S_q}{\lambda c_{pp} m} \right) \dot{m} \tag{5.66}$$

In terms of the fractional evaporation E

$$m = m_o \, (1 - w_{\ell o} E) \tag{5.67}$$

$$\dot{m} = m_o \, w_{\ell o} \frac{dE}{dt} \tag{5.68}$$

where $w_{\ell o}$ is the initial liquid mass fraction,

hence equation 66 becomes:

$$\frac{dT_p}{dE} = \frac{(S_q - S_m)\ w_{\ell o}}{\lambda\, c_{pp}(1-w_{\ell o}E)} \qquad (5.69)$$

an equation independent of time t .

II.6 Presence of solids

The manner in which solids affect the evaporation behaviour depends on what form the solid-liquid dispersion takes: a suspension, a colloidal dispersion, a solution, or a combination of the three. Once the droplet has consolidated, the microstructure and hygroscopic properties of the solid will determine the subsequent drying pattern.

II.6.1 Particle formation

In the first stages of evaporation, the droplet shrinks freely as does a pure liquid droplet. In some cases crystals may form at various places [C3], in others a flexible membrane may form on the surface (for example with emulsions such as milk), but these at first do not hinder the shrinking.

At a certain value of the (dry basis) moisture content X_{cr} , the droplet rather suddenly forms a crust (figure 2). This moisture content X_{cr} is strongly dependent on the initial moisture content X_o , as shown in figure 3 for two slurries (experimental details for the present work on zinc oxide slurry can be found in Appendix B.III). For a short time, surface-tension forces cause a temporary shrinking of the particle, at the moment when the moisture is in a pendular state, i.e. forms wedges between solid elements. This can be observed in figure 2. The value of X_{cr} probably also depends on the drying rate, but little work has been done on this.

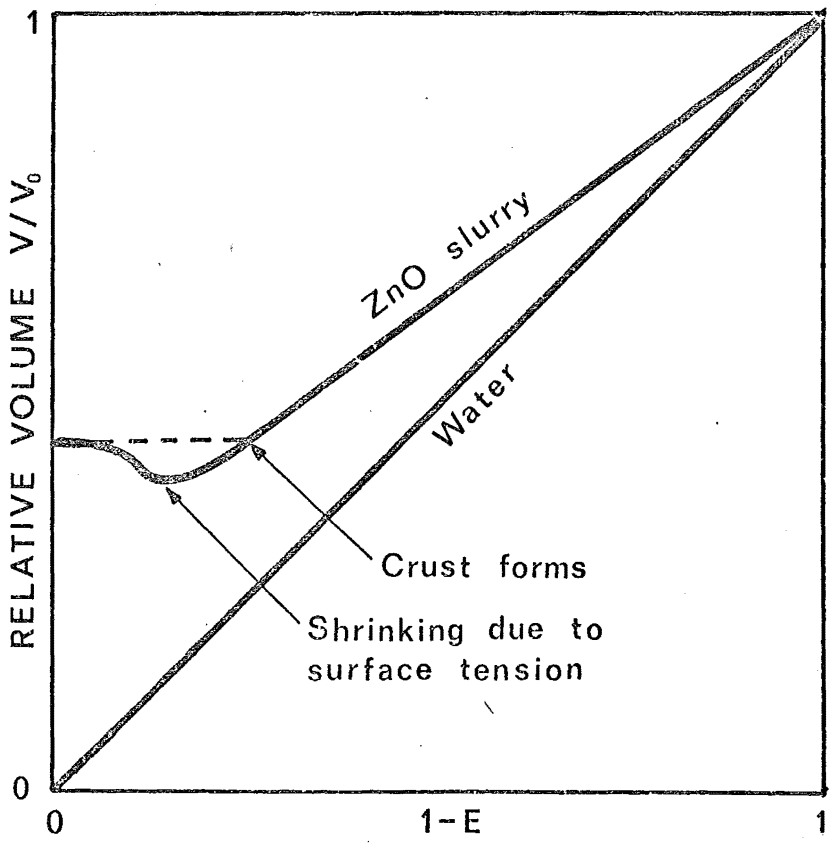


FIGURE 5.2 : SHRINKING OF A DROPLET OF ZINC OXIDE SLURRY

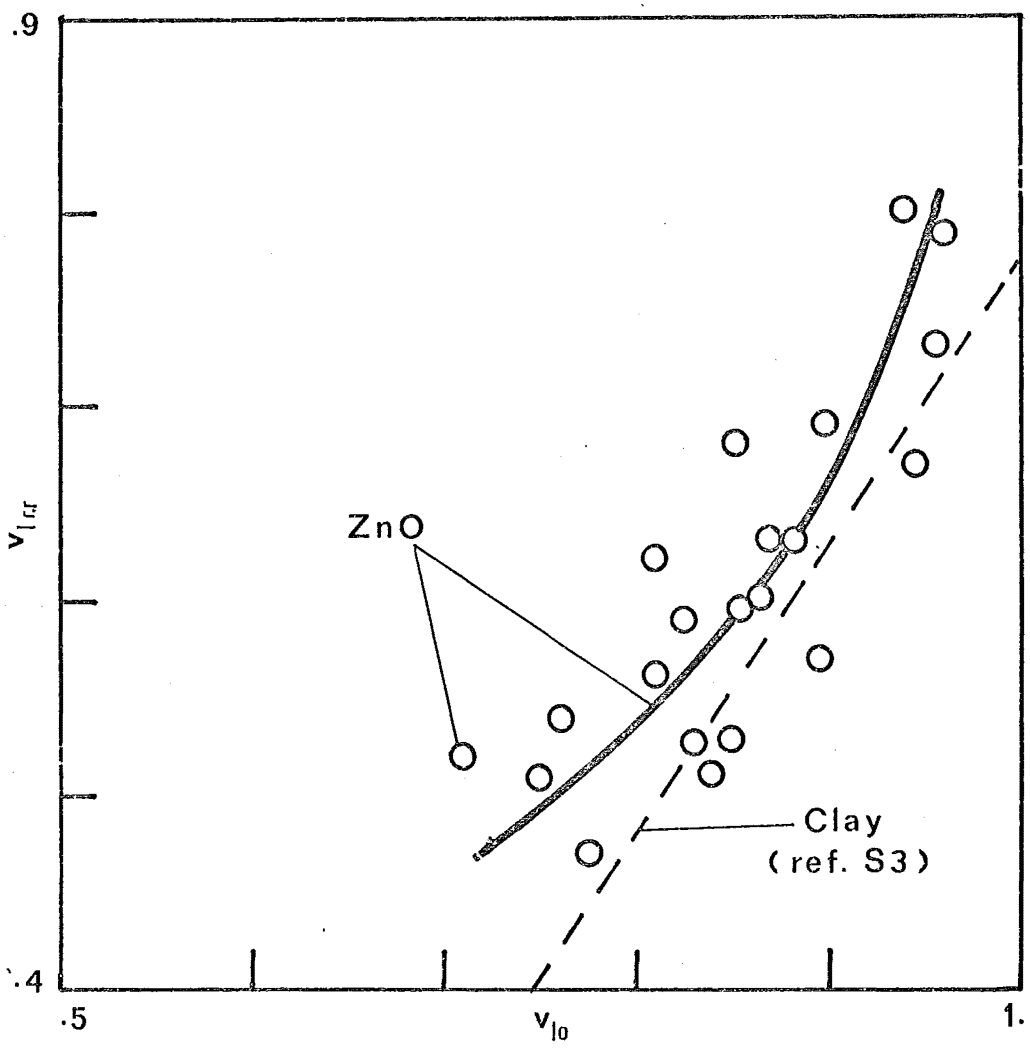


FIGURE 5.3: DEPENDENCE OF CRITICAL LIQUID VOLUME FRACTION ON INITIAL VOLUME FRACTION FOR SLURRIES

Once the crust has formed, it can either remain unchanged (rigid porous crust) or undergo deformations (C3, P8). If the drying air is above boiling point, the particle may inflate, fracture, explode, or fracture and collapse repeatedly due to the bubbling inside it. If the air is below boiling point, fracture, collapse or shrivelling may occur.

II.6.2 Drying behaviour

(a) Prior to particle consolidation:

Suspensions of solids do not have any effect in the stage before consolidation. Colloidal emulsions may form a membrane which hinders evaporation at an early stage, as data on milk demonstrate (T7, C1). True solutions will lower the vapour pressure at the surface, and thus lessen the evaporation (Henry or Raoult's law). This effect depends on the surface concentration of the solute, c_R, but the relationship of this concentration to the mean concentration $\bar{c}$ is unclear. If evaporation is fast and diffusion in the liquid slow, c_R will be close to its saturation value c_s. In the opposite case, or when there is internal convection, $c_R \simeq \bar{c}$. Approximate theoretical solutions have been obtained (C3, S3) but experimental results (C3, R4, S3) are inconclusive, and both limiting cases as well as variations between them have been observed, depending on the material tested, the initial mean solid concentration, the rate of evaporation, and other process conditions.

(b) After particle consolidation:

Drying behaviour differs markedly for porous and non-porous materials, and for hygroscopic and non-hygroscopic ones (K3). In non-porous materials, moisture migrates by diffusion and an analytical treatment is relatively easy (B10). For non-hygroscopic, capillary-porous

materials, the drying pattern has been studied analytically by Keey and Suzuki [K4] for example, and for hygroscopic capillary-porous materials Berger and Pei [B8] have done a numerical study. Out of their results the following general conclusion can be drawn, that the relative drying rate f_d ,

$$f_d \equiv \frac{\text{evaporation from particle}}{\text{evaporation from liquid droplet}} \tag{5.70}$$

at any particular instant depends on the moisture profile in the particle, which in turn depends on the following factors:

(1) External factors:

- The Biot number for heat transfer: $Bi_h \equiv \frac{hD_p}{k_p}$

- The Biot number for mass transfer: $Bi_m = \frac{k_c D_p}{\kappa_p}$

where h and k_c are the heat and mass transfer coefficients, k_p the particle thermal conductivity and κ_p the thermal diffusivity of the solid.

(2) Internal factors:

- The sorption curve.
- Luikov number for liquid movement in the particle: $Lu_\ell = \frac{\mathcal{D}_\ell}{\kappa_p}$.
- Luikov number for vapour diffusion in the particle: $Lu_v = \frac{\mathcal{D}_v}{\kappa_p}$

  where $\mathcal{D}_\ell$ and $\mathcal{D}_v$ are the diffusivities of the liquid and vapour within the particle.

(3) History: the past history of drying,- for example the mean rate of evaporation and the initial moisture, - determines the moisture profile.

In practical terms, the foregoing influences can be summed up in the equation:

$$f_d = f_d(D_p , X_o , \bar{\dot{X}} , X , \text{material}) \qquad (5.71)$$

where $\bar{\dot{X}}$ is the mean evaporation rate up to the moment the relative drying rate falls to f . The actual form of the function f must usually be determined experimentally for each material.

Hypothetical drying curves to illustrate the various drying period for the general case are shown in figure 4. The shapes of the final falling rate period are taken from reference K3.

II.7 Drop mechanics

A liquid droplet behaves differently from a solid particle because it is subject to distortion, oscillations and internal circulation. These phenomena have been studied by Garner and Lane (G5), Hughes and Gilliland (H23) and others.

Using dimensional analysis, the factors governing distortion and oscillations have been shown to be the Reynolds number Re and the surface tension number $Su \equiv \sigma \rho_c D_p/\mu_c^2$, where σ is the interfacial tensionand the subscript c refers to the continuous phase. At terminal velocitythese two terms can be combined into the Bond number, $Bo = g(\rho_d - \rho_c) D_p^2/\sigma$, where ρ_d is the disperse phase density. The oscillation frequency n is governed by Lamb's equation:

$$n = \sqrt{\frac{8\sigma}{2\pi m}} \qquad (5.72)$$

where m is the mass of the droplet. Internal circulation is a function of Re, Su and the viscosity ratio μ_c/μ_d .

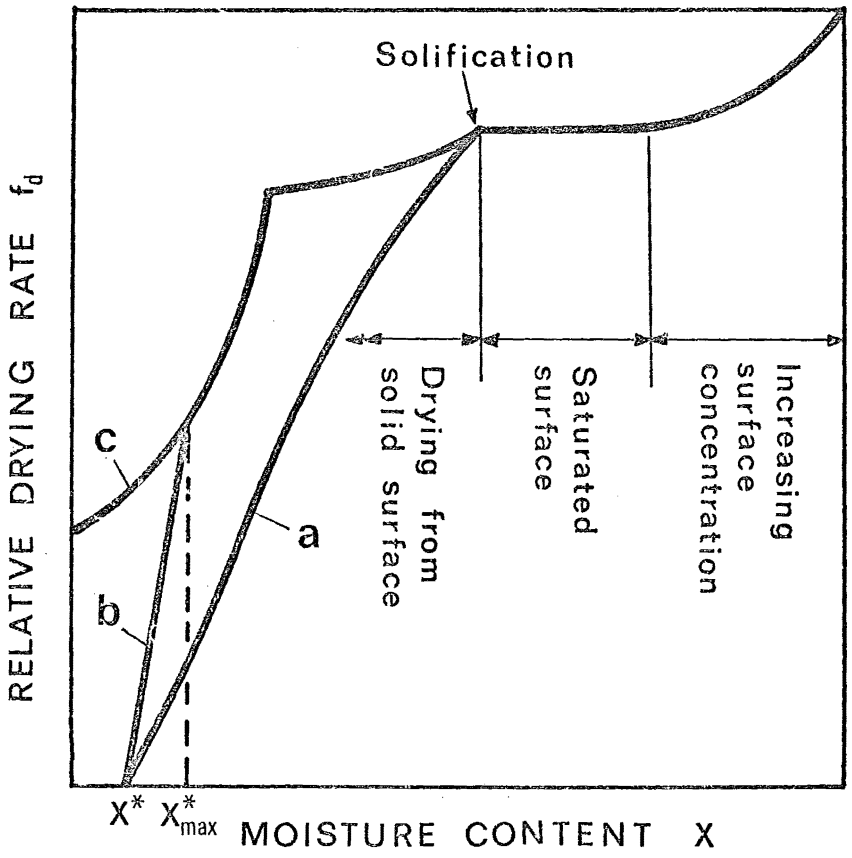


FIGURE 5.4: DRYING CURVE OF DROPLETS CONTAINING SOLIDS

(a) hygroscopic non-porous solid

(b) hygroscopic porous solid

(c) non-hygroscopic capillary-porous solid

The effects of these phenomena are:

(a) Reduction of drag coefficient: Bond and Newton [B13] showed theoretically that for creeping flow the terminal velocity is increased by a factor

$$K = \frac{1 + \mu_c/\mu_d}{1 + 2\mu_c/3\mu_d} \quad . \tag{5.73}$$

Ingebo [I 1] found that droplets accelerated in air streams obey the equation:

$$c_D = 27\ Re^{-.84} \tag{5.74}$$

which gives a lower drag coefficient than the standard drag curve for the range studied. However, he was working with clouds of droplets, which could have some effect on the apparent drag due to droplet interaction. Brehaut [B17], on the other hand, found no evidence of the effect of internal circulation.

(b) Changes in the solute concentration profile: Internal circulation, by mixing the contents of the drop, bring the surface solute concentration closer to the mean concentration. This will increase the mass transfer rate [G5, P12], retard the formation of a crust [S3] and diminish the thermal degradation of the final product. Evidences of this effect in industrial spray dryers [S1] are, however, scant and inconclusive, in view of the high viscosities of the materials sprayed.

(c) Splitting of drops: When the oscillation amplitude is too large, the droplet will break up [H10]. The parameters governing this phenomenon are Su, μ_c/μ_d and the Weber number $We \equiv \tau D_p/\sigma$, where τ is the shear stress. In a turbulent field it can be deduced that splitting occurs when

$$D_p \left(\frac{\rho_c}{\sigma}\right)^{3/5} \varepsilon^{2/5}$$

reaches a certain critical value, a result which has been experimentally verified. Here ε is the energy dissipation rate per unit mass.

The presence of solute even in small quantities will alter μ_d and σ greatly, and often inhibit the behaviour mentioned above.

NOTATION FOR CHAPTER 5

c concentration, [kg/m^2]

c_D drag coefficient, [-]

c_p specific heat, [J/kg K]

D_p particle or droplet diameter, [m]

D_h 4 x Volume/ Area = hydraulic diameter, [m]

$\mathcal{D}_{AB}$ diffusivity, [m^2/s]

E fractional evaporation, [-]

F 1-E = fraction unevaporated, [-]

f_d dimensionless or relative drying rate (eqn.70), [-]

F_D drag force, [N]

g gravitational acceleration, [m^2/s]

h heat transfer coefficient, [$W/K\ m^2$]

h_o heat transfer coefficient at zero mass flux, [$W/K\ m^2$]

I intensity of light, [W/m^2]

k thermal conductivity, [W/mK]

K_e extinction coefficient, or projected particle area per unit cloud volume, [m^{-1}]

k_c mass transfer coefficient, [m/s]

L_b mean beam length, boundary to boundary (eqn.47), [m]

L'_b mean beam length, particle to boundary, [m]

m particle or droplet mass, [kg]

$\dot{m}$ mass transfer rate, [kg/s]

n frequency of oscillation, [s^{-1}]

q heat transfer rate to particle or droplet, [W]

q_R " " " " " " " by radiation, [W]

$q_{w \to c}$ net radiation from wall to cloud of particles, [W]

Notation for Chapter 5 cont.

S view factor in radiation, [-]

S_R relative heat transfer rate when droplet is overheated, (section II.5), [-]

S_m relative mass transfer rate when droplet is overheated, (section II.5), [-]

t time, [s]

t_p particle time constant, [s]

t_L Langrangian time scale of turbulence, [s]

u velocity [m/s]

u_R relative velocity between particle and fluid, [m/s]

u' turbulent rms velocity, [m/s]

V_c cloud or chamber volume, [m^3]

v_ℓ volume fraction of liquid in liquid-solid dispersion, [-]

w_ℓ, w_s liquid, solid mass fraction, [-]

x distance, [m]

x mole fraction, [-]

X dry basis moisture content [-]

X_{cr} dry basis moisture content at droplet solidification, [-]

y air humidity dry basis, [-]

α emissivity or absorptivity of radiation, [-]

β $(Nu-2)/ Re^{1/2}Pr^{1/3}$ or $(Sh-2)/Re^{1/2}Sc^{1/3}$, [-]

ε turbulent energy dissipation rate per unit mass, [W/kg]

κ heat diffusivity, [m^2/s]

λ latent heat of evaporation, [J/kg]

μ viscosity, [kg/ms]

ν kinematic viscosity, [m^2/s]

π 3.14159...

Π $c_D Re^2$, [-]

Notation for Chapter 5 cont.

ρ density, [kg/m^3]

σ surface tension, [N/m]

σ Stefan-Boltzmann's constant, [W/m^2K^4]

τ shear stress, [N/m^2]

Dimensionless numbers

B $\frac{C_{pv}\Delta T}{\lambda}$ = Spalding's number

Bi_h $\frac{hD_p}{k_p}$ = Biot's number for heat transfer

Bi_m $\frac{k_c D_p}{\kappa_p}$ = Biot's number for mass transfer

Bo $\frac{g\Delta\rho D_p^2}{\sigma}$ = Bond number

Lu $\frac{\mathfrak{D}}{\kappa}$ = Luikov number

Nu $\frac{hD_p}{k_f}$ = Nusselt number

Nu_o Nu at zero mass flux

Pr $\frac{\mu_f c_{pf}}{k_f}$ = Prandtl number

Re $\frac{D_p u_R \rho_f}{\mu_f}$ = Reynolds number

Sc $\frac{\nu_f}{\mathfrak{D}_{AB}}$ = Schmidt number

Sh $\frac{k_c D_p}{\mathfrak{D}_{AB}}$ = Sherwood number

Notation for Chapter 5 cont.

Su $\frac{\sigma \rho_c D_p}{\mu_c^2}$ = Surface tension group

We $\frac{\tau D_p}{\sigma}$ = Weber number

Wt $\frac{g(\rho_d - \rho_c) D_p^2}{\sigma}$ = Weight group

Subscripts

a air

c continuous phase

c cloud

cr critical, at droplet solidification

d dispersed phase

f fluid

g gas

i in the i-th direction

ℓ liquid

p particle, droplet

R relative (velocity)

R at droplet radius or surface

s solid

s surface

t terminal

v vapour

w wall

w→c wall to cloud

wp wall to particle (view factor)

o initial (at t=o or x=o)

∞ at infinite distance, in the surroundings

Superscripts

* equilibrium, saturation

' turbulent (rms)

$\bar{}$ mean

· rate of change

CHAPTER 6

SPRAY DRYER DESIGN AND PERFORMANCE

Chapter contents:

INTRODUCTION

The spray drying process consists of three main steps:

1. Atomisation
2. Evaporation and drying
3. Product collection.

This chapter is mainly concerned with the second step, that is: what happens to the droplets once they leave the atomiser and until they emerge from the drying chamber. However, the atomisation process will also often have to be considered, since it supplies the initial conditions of the drying history of the spray.

A short review of available spray-evaporation calculation methods will be carried out, followed by a computer simulation of cocurrent spray dryers with nozzle atomisers. Finally, the influence of air and spray residence time distributions will be discussed.

I. A REVIEW OF METHODS FOR SPRAY DRYER DESIGN AND PERFORMANCE PREDICTION

Until recently, the state of the art of spray dryer design was, in the words of an engineer in the field, "to build it and make it work". There has been no unified approach and probably never will be, as spray-drying situations vary greatly and the interacting factors are too complex. Most of the methods proposed so far are only tentative and insufficiently proven. A classification of available methods is shown in Table 1.

TABLE 6.1

CLASSIFICATION OF SPRAY-DRYER DESIGN OR PERFORMANCE PREDICTION METHODS

1.	Empirical or semi-empirical methods:	
		Luikov, Feder, Borde, Dolinsky
2.	Analytical methods:	
	1. Based on one droplet size:	Johnstone & Eads, Miesse, Sjetnitzer, Gluckert.
	2. Based on a size spectrum:	Schlünder, Marone, McIlvried & Massoth.
	First-order reaction methods:	Shapiro & Erickson, Hopkins & Eisenklam, Dombrowski & Johns.
3.	Numerical (stepwise) methods:	Marshall, Dickinson & Marshall, Leonchik, Katta & Gauvin, Parti & Palancz, Weber & Viehweg.

I.1 Empirical and semi-empirical methods

Luikov[L10] gave an empirical equation for the volumetric heat transfer coefficient as a function of droplet mean diameter, droplet velocity and other parameters. Turba and Nemeth[T8] found that this equation gave a prediction for their spray dryer which was out by a factor of 10.

Feder[F1] gave a graphical method based mainly on empirical data. Borde[B14] derived a design equation based on dimensional analysis, but did not give any explicit solution. Dolinsky[D9] followed a similar approach, but arrived at explicit equations for the dimensions of a dryer with disk atomiser and cocurrent flow of spray and air. He made the assumption that: $Nu = 2$.

Due to the diversity of spray drying systems (geometry, operating ranges, feed materials ...) and the numerous simplifying assumptions that must be made in order to arrive at any "general" equation, it can safely be said that the above-mentioned methods are of little practical use, and can at best give some qualitative idea of the effects of some variables.

I.2 Analytical methods

I.2.1. Methods which consider one drop size

Several authors have tried to replace the polydisperse spray by a single droplet size, usually the maximum size produced by the atomiser. The equations of motion and evaporation for this size can then be solved, with the initial conditions given by the atomising method used.

Sjetnitzer[S11] gave his results as graphs. He assumed constant air conditions, pure liquid droplets, Ranz and Marshall's equation for heat and mass transfer:

$$Nu = 2 + 0.6\ Re^{1/2} Pr^{1/3} \quad ,$$

and Ingebo's equation for the drag curve:

$$c_D = 27\ Re^{-.84} \quad . \qquad (6.1)$$

He also derived[S10] an equation for the height of transfer unit of a spray dryer based on some mean evaporative diameter.

Johnstone and Eads[J3] derived a relationship for the lifetime of a pure liquid drop. Their assumption of constant relative velocity between drop and gas restricts its usefulness. Miesse[M14] solved the equations of motion and evaporation for a pure liquid drop in constant, decelerating and accelerating gas flows. His assumptions were a Stokes flow regime and Nu = 2.

Schlünder[S3] also studied the drying history of individual droplets. Gluckert[G9] proposed basing the design of spray dryers on the maximum droplet diameter D_m , which he took to be:

$$D_m = 3\,\bar{D}_{vs} \quad .$$

Using available relationships in the literature for the effect of atomising conditions on the initial droplet sizes and velocities, he arrived at equations for the design of spray dryers with disk, twin-fluid and pressure atomisers.

At first sight it would appear that replacing the spray by a single droplet size is a rather crude assumption. However, as will be seen later, the largest drops are in fact the determining factor for the design and operation of spray dryers in most cases. Thus the foregoing methods can be useful, although for a more accurate calculation one needs to consider further the mechanics of drying; most of the methods so far are only for pure liquids.

I.2.2. Analytical methods which treat a size spectrum

I.2.2.1 General approach:

In the following methods the evaporation of each sized droplet is integrated over the whole size spectrum to yield the total evaporation. Probert[P13] was the first to make this approach. Shapiro and Erickson[S8] developed a general differential equation for a cloud of particles or droplets undergoing evaporation or combustion and acceleration. By a numerical accounting of droplets with a given size, position and velocity, they showed that:

$$\frac{\partial \mathcal{G}}{\partial t} + u_p \frac{\partial \mathcal{G}}{\partial x} + \mathcal{R} \frac{\partial \mathcal{G}}{\partial D_p} = -\mathcal{G}\left[\frac{\partial u_p}{\partial x} + \frac{u_p}{A}\frac{dA}{dx} + \frac{\partial \mathcal{R}}{\partial D_p}\right] \qquad (6.2)$$

where A is the flow area of the cloud, $\mathcal{R}$ is the growth rate of the particles ($\mathcal{R} = dD_p/dt$), $\mathcal{G}$ is the number-size distribution ($\mathcal{G} = dn/dD_p$), u_p the particle velocity ($u_p = dx/dt$) and $\mathcal{R}$, u_p, $\mathcal{G}$ are all functions of the diameter D_p. Williams [W5] also gave a similar equation.

By assuming some form of $\mathcal{R}(D_p)$, $u_p(D_p)$ and $\mathcal{G}(D_p)$, equation 2 can be solved for the entire spray. dA/dx is generally assumed to be 0, and in most treatments du_p/dD_p is assumed to be zero also (uniform cloud motion), so that only $\mathcal{R}(D_p)$ and $\mathcal{G}(D_p)$ have to be assumed.

For $\mathcal{G}(D_p)$ being a normal distribution, Schlünder [S3 § 5.321] tried several different power laws for the growth rate

$$\frac{dD_p}{dt} \propto - D_p^{-\gamma} \tag{6.3}$$

and arrived at semi-analytical expressions for the evaporation history. These are quite complex and make extensive use of uncommon tabulated functions.

Marone [M4], assuming a constant Nusselt number and a Rosin-Rammler size distribution (equation 18), arrived at an integral equation which has to be solved numerically. Yaron and Gal-Or [Y1] also made an analytical study of transfer phenomena with size-distributed systems which can be applied to spray drying. One interesting work is that of McIlvried and Massoth [M10] who studied a single particle and clouds of solid particles reacting with a gas. The reaction is assumed to be controlled by solid-phase diffusion and the results may be useful for the cases where drying proceeds well into the falling-rate period.

However, due to the complexity of those solutions, several authors have purposely chosen expressions for $\mathcal{R}(D_p)$ and $\mathcal{G}(D_p)$ to get simpler results. The next section examines in some detail a class of methods which may be of particular use when we come to the study of the

effects of deviations from plug-flow and residence time distributions.

I.2.2.2 Constant evaporative diameter or first-order reaction methods:

A first-order reaction has a rate equation of the form[L6] :

$$-\frac{dc_A}{dt} = k_1(c_A - c_{Ae}) \tag{6.4}$$

where c_A is the concentration of reactant A, c_{Ae} its equilibrium value, k_1 the rate constant. This type of reaction is particularly amenable to mathematical treatment. In particular, their yield in a reactor is independent of the actual mixing pattern and depends only on the residence time distribution (RTD) curve C(t) :

$$\frac{c_{A2} - c_{Ae}}{c_{A1} - c_{Ae}} = \int_0^\infty e^{-k_1 t} C(t)dt$$

$$= \text{L.T. } \{C(t)\} \tag{6.5}$$

(neglecting end effects), where c_{A2} and c_{A1} are the outlet and inlet values of c_A respectively, and L.T. is the Laplace Transform.

Because of this mathematical simplicity, many workers have tried to approximate the process of evaporation by a first-order reaction. The reasoning is as follows: as the smaller droplets evaporate very quickly, they soon disappear from the evaporation process and leave behind the larger droplets. Thus, although all droplets are shrinking, their mean evaporative diameter (M.E.D.) and hence their specific (per unit remaining mass) evaporation are constant.

The M.E.D., D_e , is the diameter of a pure liquid droplet which has the same evaporation rate k_1 per unit (remaining) liquid mass:

$$k_1 = \frac{(\pi/2)\ D_e^{\,2}\ \mathcal{R}(D_e)}{(\pi/6)\ D_e^{\,3}} = \frac{\int_0^\infty (\pi/2)\ D_p^{\,2}\ \mathcal{R}(D_p)\ \mathcal{G}(D_p)\ dD_p}{\int_0^\infty (\pi/6)\ D_p^{\,3}\ \mathcal{G}(D_p)\ dD_p} \tag{6.6}$$

with $\mathcal{R}(D_p)$ and $\mathcal{G}(D_p)$ defined as in equation 2.

In particular if

$$\mathcal{R}(D_p) = - K D^{-\gamma} \tag{6.7}$$

then

$$D_e = \left[\frac{\int_0^\infty D_p^{\,3} \mathcal{G} dD_p}{\int_0^\infty D_p^{\,2-\gamma} \mathcal{G} dD_p} \right]^{\frac{1}{1+\gamma}} = \bar{D}_{3,2-\gamma} \tag{6.8}$$

and

$$k_1 = 3 K D_e^{-(1+\gamma)} \tag{6.9}$$

where $\bar{D}_{m,\,n}$ is the m-n mean diameter[M16].

Whether k_1 and D_e remain constant with time obviously depends on the form of $\mathcal{R}(D_p)$ and $\mathcal{G}(D_p)$, as can be seen from equation 2. Shapiro and Erickson[S8] showed that if

$$\mathcal{G} \propto D_p\, e^{-KD_p^{\,2}} \tag{6.10}$$

and

$$\mathcal{R} \propto - D_p^{-1} \tag{6.11}$$

(the latter equation implying Sh = Nu = constant), then D_e and k_1 are constant.

Hopkins and Eisenklam[H19] extended this method and showed that the same result is obtained whenever

$$\mathcal{G} \propto D_p^{\,n-1}\, e^{-KD_p^{\,n}} \tag{6.12}$$

and

$$\mathcal{R} \propto - D_p^{1-n} \tag{6.13}$$

This may be shown by solving equation 2. They suggested n = 1.55 for burning oil sprays.

Dombrowski and John[D11] used a polynomial form for the size distribution

$$\mathcal{G} = a + b D_p^{\,2} + c D_p^{\,5} + d D_p^{\,8} \tag{6.14}$$

and equation 11 for $\mathcal{R}$, and found that $D_e = \bar{D}_{31}$ remains roughly constant for up to 90% evaporation in pure liquid sprays. In fact they showed that

$$\frac{k_{10}}{k_1} = \left(\frac{D_e}{D_{eo}} \right)^2 = 1.1(1-E)^{0.13} \tag{6.15}$$

where E is the fractional evaporation.

Critical examination of the constant M.E.D. methods:

Thus far all these methods have assumed certain forms of the size-distribution equation which are not widely accepted. The most common equations for the size distribution are:(M16)

(1) Log-normal (L.N.) distribution:

$$\frac{dv}{d(\ell n D_p)} = \frac{1}{\sqrt{2\pi}\,\sigma_{LN}} \exp\left[- \frac{(\ell n D_p - \mu_{LN})^2}{2\sigma_{LN}^2} \right] \tag{6.16}$$

(2) Root-normal (R.N.) distribution:

$$\frac{dv}{d(\sqrt{D_p})} = \frac{1}{\sqrt{2\pi}\,\sigma_{RN}} \exp\left[- \frac{(\sqrt{D_p} - \mu_{RN})}{2\sigma_{RN}^2} \right] \tag{6.17}$$

where μ_{LN}, μ_{RN}, σ_{LN}, σ_{RN} are the means and standard deviation of $\ell n\, D_p$ and $\sqrt{D_p}$ respectively, and v is the volume fraction under size D_p.

(3) Rosin-Rammler (R.R.) distribution:

$$\frac{dv}{dD_p} = K D_p^{\delta-1} \exp\{- a D_p^{\delta}\} \tag{6.18}$$

(4) Nukiyama-Tasanawa (N.T.) distribution:

$$\frac{dv}{dD_p} = K D^5 \exp\{- a D_p^{\delta}\} \tag{6.19}$$

where δ is the dispersion index.

In order to see how the constant M.E.D. assumption holds for these four distributions in the case of constant Nusselt number (equation 11), a numerical computation of the variation of the specific evaporation rate was carried out. σ_{LN}, σ_{RN} and δ for equations 18 and 19 were varied. The procedure followed was a simplified version of Marshall's stepwise method described in the next section, and the results are plotted as f_c against E, where:

$$f_c \equiv \frac{k_1}{k_{10}} \equiv \left(\frac{D_e}{D_{eo}}\right)^{-2} .$$

If f_c is constant, then the M.E.D. is also constant. The results are shown in Figure 1. An alternative approach would be to plot ℓn F against t, where $F \equiv 1-E$, and see if the graph is linear. These plots can be found in reference D5. In practice one would be content with a 10% variation in f_c .

It can be seen from figure 1 that the constant M.E.D. assumption holds only for a limited range of σ_{LN}, σ_{RN} or δ , and up to a certain value of E. The values of the dispersion parameters for best approximation are:

N.T. distribution: $\delta = 1.5 - 1.8$

R.R. distribution: none

R.N. distribution: $\sigma_{RN}/\mu_{RN} = .15 - .17$

L.N. distribution: $\sigma_{LN}/\mu_{LN} = .25 - .35$

The presence of solids may or may not have an important effect on the foregoing results, depending on how the material behaves. Two criteria must be considered: whether the solid forms a crust at an early or late stage, and whether it hinders the evaporation by resistance to moisture transfer.

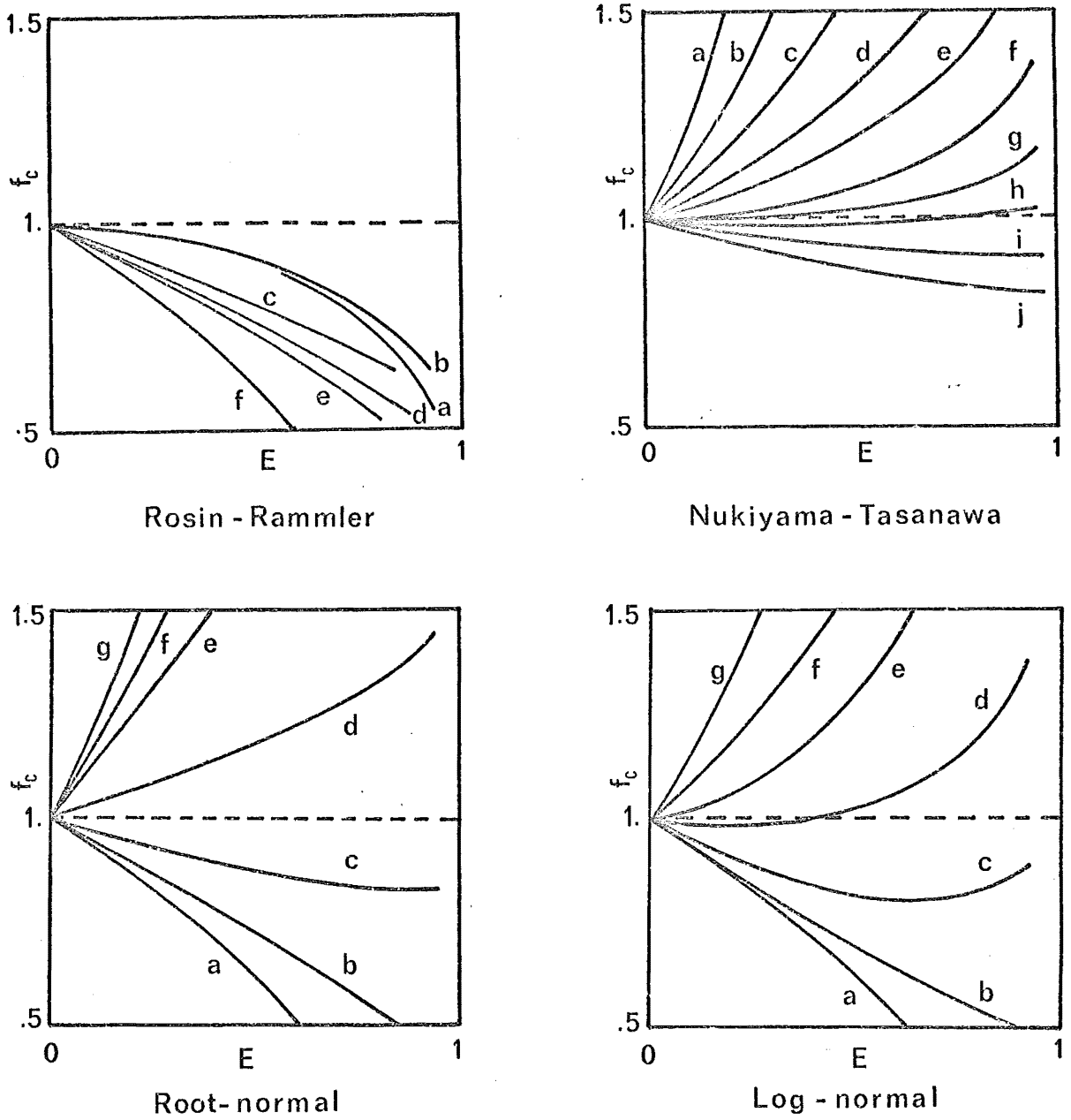


FIGURE 6.1: VARIATION IN SPECIFIC EVAPORATION RATE FOR SOME SPRAYS

Rosin-Rammler distribution: value of δ:

(a) 2.0 (b) 2.3 (c) 3.2 (d) 3.8 (e) 4.4 (f) ∞ (monidisperse spray).

Nukiyama-Tasanawa distribution: value of δ :

(a) 0.2 (b) 0.4 (c) 0.6 (d) 0.8 (e) 1.0 (f) 1.2 (g) 1.4 (h) 1.6 (i) 1.8 (j) 2.0.

Root-normal distribution: value of σ_{RN}/μ_{RN} :

(a) 0 (monodisperse spray) (b) 0.10 (c) 0.15 (d) 0.20 (e) 0.25 (f) 0.30 (g) 0.40.

Log-normal distribution: value of σ_{LN}/μ_{LN} :

(a) 0 (monodisperse spray) (b) 0.2 (c) 0.3 (d) 0.4 (e) 0.5 (f) 0.6 (g) 0.8 .

Consider the following extreme cases:

(1) Immediate forming of crust, no hindering of evaporation (thick slurry of non-hygroscopic coarse-grained material): moisture evaporates from the droplet surface at a constant rate, i.e. k_1 increases with time.

(2) Immediate forming of crust, appreciable hindering of evaporation: the change in k_1 will depend mainly on the characteristic drying curve of the material, and not on the size distribution. This is an important case in industrial spray drying, but has not received much attention up to now.

(3) Late forming of crust, late hindering of evaporation: there will be little change in the behaviour of f_c, D_e or k_1 (this has been checked by a numerical calculation similar to the one mentioned earlier).

Apart from the restrictions already mentioned, the usefulness of constant M.E.D. methods is limited by the following underlying assumptions:

(1) The particles move in a uniform manner, with no differential velocity.

(2) Nu = constant (except in the case of Hopkins and Eisenklam's method).

(3) Constant drying conditions (this restriction can be waived, but this leads to complex results).

(4) Little effect of the presence of solids on the evaporation and shrinking of the droplets.

(5) An infinite maximum droplet size (except in Dombrowski and Johns' method).

Assumptions (1) and (2) mean that these methods apply only to fine sprays, perhaps $D_{max} < 40$ µm.[D7] In industry, fine products are often not desirable for reason of coagulability, handling

difficulties and losses. Assumption (4) is similarly unrealistic in most cases. When assumption (5) does not hold and there is a finite maximum diameter, the M.E.D. will decrease more quickly than predicted towards the end of evaporation. Finally, the author has found that many sprays generated by nozzles have a Nukiyama-Tasanawa distribution with $\delta \simeq 0.5$, for which D_e does not remain constant.

For these reasons, the methods considered can be used (in the best cases) only in the early stages of evaporation, say for $E < .8$. Thus they may be applicable in spray-cooling towers, or perhaps in combustion chambers. In spray drying, one is mainly interested in the later stages, where $E \simeq 1.$, $F \simeq 0.$, and product quality may be quite sensitive to variations in F. Thus if $E = .95$, a 1% error in E means a 20% error in F, and no analytical method would be even that accurate.

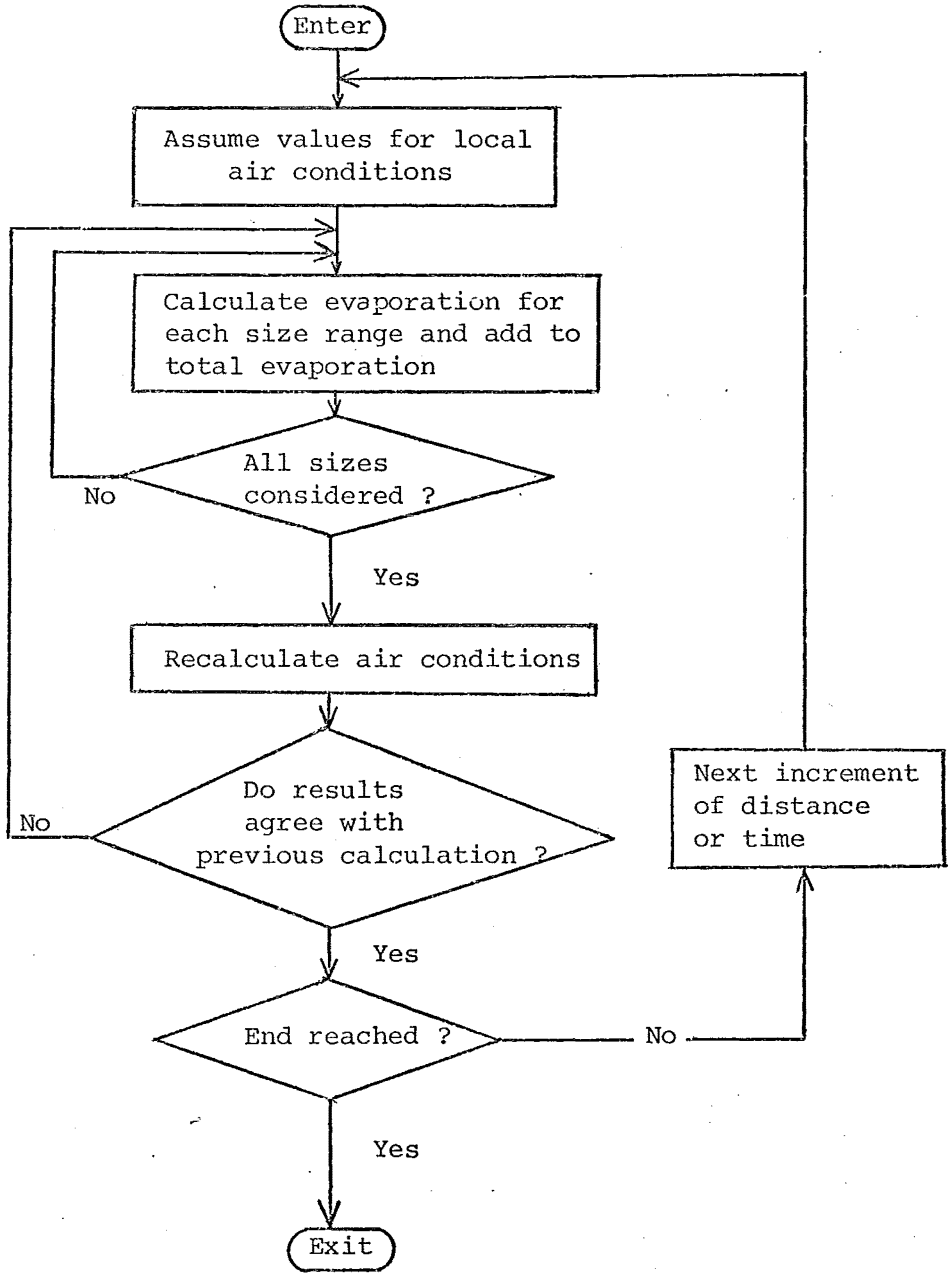
I.3 Numerical (stepwise) methods

When computers are available, the most obvious approach is to calculate the evaporation of each size range in the spray for a given increment of time or space, sum up over all size ranges to get the total evaporation, and go on to the next increment. Size ranges are based on the initial sizes and not on the instantaneous size, so that each group of droplets is followed throughout its history. When the air-spray rate ratio is small, the evaporation may have an appreciable effect on the air conditions, so an iteration process at each point may be necessary. A simplified flow diagram is shown in figure 2.

Such a method was first proposed by Marshall[M6] and used with various modifications by Dickinson and Marshall[D5], Leonchik[L4], Dloughy and Gauvin[D7, D8], Gauvin and Katta[K1, G6], Hoffmann and Gauvin[H15], Weber, Viehweg and Biess[V2,W2], Parti and Palancz[P3].

Figure 6.2

Simplified flow diagram for stepwise calculation of spray evaporation



Numerical methods are in general very flexible, a great number of influences can be taken into account and, provided the basic assumptions are sound, the results should be fairly accurate[D7, K1]. This flexibility should make up for the lack of generality of the results.

One of the most recent programs available is that of Katta and Gauvin who considered short-form spray dryers with tangential air inlet.

In the next section, a program will be developed to consider tall-form cocurrent spray dryers with predominantly axial air inlets.

II. A NUMERICAL SIMULATION OF SPRAY DRYING

A computer program was written essentially along the lines of Marshall's method (figure 2), but incorporating several factors which may be of importance in industrial situations. The configuration considered is that of a cocurrent tall-form drying chamber, with a pneumatic or pressure atomiser.

II.1 Theoretical considerations

II.1.1 Hydrodynamic profile

II.1.1.1 Existence and extent of a jet zone

Visual observations made on our spray dryer as well as those made by others[G6, K1] point to the existence of two quite different hydrodynamic zones through which the droplets must travel: a jet zone and a main zone. In the latter, spray-air mixing is complete (to within the limit imposed by the chamber geometry and drying-air flow pattern) and the particles fall at their settling velocities. In the former, the hydrodynamic profile is governed by the characteristics of the nozzle.

In the past, many workers have ignored this zone on the grounds that droplets projected into a slower air flow will be rapidly decelerated to their terminal velocity, as shown by the equations of Lapple and Shepherd[L2] and Sjetnitzer[S11]. For instance, in the Stokes regime, a particle projected into a quiescent fluid will travel at an exponentially decreasing velocity

$$u_p = u_{po} \exp(-t/t_p) \tag{6.20}$$

where

$$t_p = \rho_p D_p^2 / 18 \mu_a \tag{6.21}$$

For a 40 μm water droplet in air this means that the velocity is halved every 4 ms.

However, we must take into account the fact that a swarm of droplets may travel in a fairly coherent manner, entraining the gas with them, so that they will decelerate much more slowly than a single droplet[I 1, A7]. Therefore, a closer look into jet dynamics is necessary.

The effects of the jet zone are threefold:

(1) The relative velocity between droplet and air are higher than in the main zone, due to the larger gas velocity gradient.

(2) The absolute velocity of the droplets will also be high.

(3) The confined geometry of the jet, and the limited flow of air in it, will restrict the maximum possible evaporation.

Effect (1) will tend to increase evaporation, while effects (2) and (3) will decrease it.

There is as yet no method for predicting when the jet zone stops and the main zone starts. It may be speculated that this is a function of the momentum of the jet and the turbulent intensity of the surrounding fluid, and thus interpolation between experimental data

may be possible. In the meantime, visual observations must provide the answer.

II.1.1.2 Properties of the jet zone

Jet dynamics is an extensive subject[A3, B19, B3, C9, M11]. The approach followed here will be a somewhat simplified version of Abramovitz's treatment[A3]. The simplest case is that of an axisymmetric, one-phase, incompressible submerged jet (i.e. one that is injected into quiescent fluid) with no initial radial or tangential velocity. This case will be considered first, then modifications made for an industrial situation.

(a) Single-phase submerged jet: A jet can be divided into three regions (Figure 3): an initial region with a diminishing core, a transition region, and a main region which is conical in shape (the last is not to be confused with the "main zone" of the spray dryer mentioned earlier). The first two regions are quite short. In the nomenclature of figure 3:

$$x_1 \simeq 8\, r_o \tag{6.22}$$

$$x_2 \simeq 12.4\, r_o \tag{6.23}$$

where r_o is the orifice radius, so that for our purposes the jet can be considered as consisting of its main region only. Also, the pole of the main region nearly coincides with the orifice:

$$x_o/r_o \simeq 0 \tag{6.24}$$

In the main region of the jet (from now on referred to simply as "the jet"), the jet radius R_j is proportional to the distance from the pole:

$$R_j = 0.22\,(x-x_o) \tag{6.25}$$

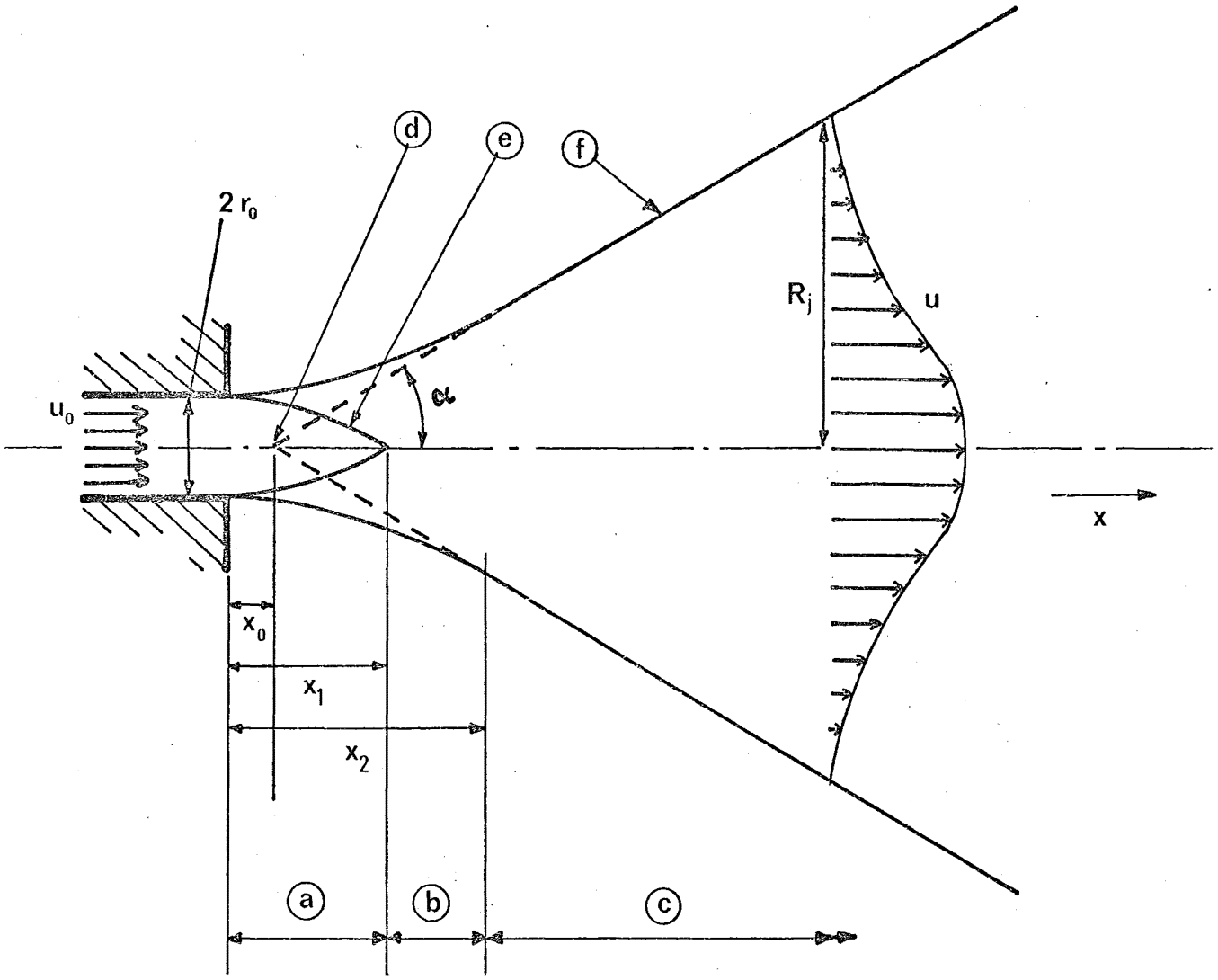


FIGURE 6.3: ONE-PHASE SUBMERGED JET

(a) Initial region
(b) Transition region
(c) Main region
(d) Pole
(e) Core
(f) Boundary of jet

so that the jet is conical and sustends a half angle

$$\alpha = \tan^{-1} 0.22 = 12.4 \text{ deg.} \tag{6.26}$$

The radial velocity profile remains similar at any cross-section, having a bell shape which can be represented either by a Gaussian function or by the formula

$$\frac{u}{u_m} = \left[1 - \left(\frac{r}{R_j}\right)^{1.5}\right]^2 \tag{6.27}$$

where u_m is the (axial) velocity at the jet axis. By conservation of momentum

$$u_m^2 R_j^2 = \text{Constant} \tag{6.28}$$

so that from equation 26

$$\frac{u_m}{u_o} = \frac{12.4\, r_o}{x - x_o} \tag{6.29}$$

The rate of air flow in the jet can be found by integrating the velocity over the jet cross-section, which gives:

$$\frac{G}{G_o} = \frac{0.14(x - x_o)}{r_o} \tag{6.30}$$

This is in satisfactory agreement with the empirical equation found by Davies[D3]

$$\frac{G}{G_o} = \frac{0.115\, x}{r_o} - 1 \tag{6.31}$$

the difference being probably due to the approximate velocity profile used.

The radial temperature profile varies as the square root of the velocity profile:

$$\frac{T - T_\infty}{T_m - T_\infty} = 1 - \left(\frac{r}{R_j}\right)^{1.5} \tag{6.32}$$

where T_m is the axis temperature and T_∞ is the surrounding-fluid temperature, and

$$\frac{T_m - T_\infty}{T_o - T_\infty} = \frac{9\, r_o}{x - x_o} \tag{6.33}$$

where T_o is the temperature of the fluid emerging from the orifice. If there is a tracer gas or a spray in the jet, then their concentration c will be similar to the temperature profile:

$$\frac{c - c_\infty}{c_m - c_\infty} = 1 - \left(\frac{r}{R_j}\right)^{1.5} \tag{6.34}$$

$$\frac{c_m - c_\infty}{c_o - c_\infty} = \frac{9\, r_o}{x - x_o} \tag{6.35}$$

where the suffixes m, ∞ and o refer to the axis, surrounding and orifice values as usual.

(b) Two-fluid jets; This is the case of pneumatic atomising nozzles. The properties of the jet will be modified by the change in mean jet density. The governing parameter here is the liquid-to-gas ratio at the orifice, and an analytical treatment was given by Abramovitz. However, in computer simulation a simpler approach can be made by recalculating the profile numerically: we shall assume a one-phase jet, calculate the momentum transfer between the air and the liquid, and modify the air velocity accordingly.

(c) Liquid jet injected into a gas: This is the case of pressure atomisers. The governing factor is now the liquid/gas density ratio

$$j = \frac{\rho_\ell}{\rho_g} \quad .$$

Equations 22, 23, 24 must be changed to:

$$\frac{x_1}{r_o} = 24 \tag{6.36}$$

$$\frac{x_2}{r_o} = 10.7\ (1.73\sqrt{j} - 1) \tag{6.37}$$

$$= 500 \quad \text{for water-air sprays} \tag{6.38}$$

$$\frac{x_o}{r_o} = \frac{x_2}{r_o} - 13.6\sqrt{j} \tag{6.39}$$

$$= 120 \quad \text{for water-air sprays} \tag{6.40}$$

The longitudinal velocity profile (equation 29) now becomes:

$$\frac{u_m}{u_o} = 2.25\ j\left(\frac{r_o}{R_j}\right)^2 \left[\sqrt{1 - 1.5\left(\frac{R_j}{r_o}\right)^2/j} - 1\right] \tag{6.41}$$

where R_j is given by the implicit equation:

$$0.22\left(\frac{x-x_o}{r_o}\right) = \frac{R_j}{r_o} + \sqrt{j}\left\{\ell n\left[1.22\frac{R_j}{r_o\sqrt{j}} + \sqrt{1 + \frac{1.48}{j}\left(\frac{R_j}{r_o}\right)^2}\right]\right.$$

$$\left. - 0.25\tan^{-1}\left[1.28\frac{R_j}{r_o\sqrt{j}}\frac{1 + \frac{1.48}{j}\left(\frac{R_j}{r_o}\right)^2 - 0.24}{\sqrt{1 + \frac{1.48}{j}\left(\frac{R_j}{r_o}\right)^2 + \frac{0.31}{j}\left(\frac{R_j}{r_o}\right)^2}}\right]\right\} \tag{6.42}$$

At large distances x this gives a profile similar to that of one phase jets, with a half-angle of 12.4 deg.

The air flow (equation 31) now becomes:

$$G = 1.82\ u_o\ r_o^2\ j\ \rho_g\left[\sqrt{1 + \frac{1.5}{j}\left(\frac{R_j}{r_o}\right)^2} - 1\right] \tag{6.43}$$

The longitudinal temperature profile is given by:

$$\frac{T_m - T_\infty}{T_o - T_\infty} = \frac{0.75\ u_m/u_o}{1 - 0.6\ u_m/u_o} \tag{6.44}$$

and the longitudinal concentration profile by:

$$\frac{c_m - c_\infty}{c_o - c_\infty} = \frac{0.75\ u_m/u_o}{1 - 0.6\ u_m/u_o} \tag{6.45}$$

instead of eqns. 33 and 35 respectively. The radial profiles of u, T and c will of course remain the same.

(d) Jets with initial radial or tangential velocity: Pressure nozzles are often designed to give the jet an initial non-axial velocity component so that the jet angle α may be different from 12.4 deg. For full-cone jets this can be taken into account by applying the momentum conservation equation, eqn. 28, which gives

$$u_m \propto 1/R_j \tag{6.46}$$

and a correction factor can be applied to all the previous equations for the longitudinal profiles of u_m, T_m, c_m and G. In equations 29, 33, 35 and 41, the right-hand side must be divided by $(\tan\alpha/\tan(12.4\ \text{deg.}))$, while in equations 30, 31 and 43 the right-hand side must be multiplied by the same factor.

(e) Jets injected into cocurrent streams: If the velocity u_∞ of the stream is low compared to the orifice velocity, as is usually the case, we can simply replace u by $(u-u_\infty)$, u_m by (u_m-u_∞) and u_o by (u_o-u_∞) in equations 27, 29, 41. For large mainstream velocities the general profile of the jet will be stretched and more complicated equations arise [A3].

II.1.1.3 Particle behaviour in jet zone

The gas velocity in a jet is inversely proportional to the distance from the pole. The momentum, heat and mass transfer behaviour of a single liquid droplet in such a flow-field will now be briefly considered. The flow field will be somewhat simplified for the purpose of the present calculations. The equations to be solved are:

- The equation of motion:

$$\frac{du_p}{dx} = -\frac{1}{u_p}\,\frac{0.75\, c_D \rho_a}{D_p\, \rho_p}\,|u_p - u_a|\,(u_p - u_a) \qquad (6.47)$$

where c_D is the drag coefficient, u_p and u_a the droplet and air velocities respectively, ρ_p and ρ_a the droplet and air densities, and

$$u_a = u_o\,\frac{x_c}{x + x_c} \qquad (6.48)$$

where x_c is a characteristic length

$$c_D = c_D\,(D_p\,|u_p - u_a|\,/\nu_a)$$

where ν_a is the kinematic viscosity of air.

- The equation of evaporation (Ranz and Marshall type):

$$\frac{d\,D_p}{dx} = -\frac{2k_a\,\Delta T}{\rho_p \lambda D_p u_p}\left(2 + \frac{0.6\ Pr^{1/3} D_p^{1/2} |u_p - u_a|^{\frac{1}{2}}}{\nu_a^{\frac{1}{2}}}\right) \qquad (6.49)$$

where k_a is the air thermal conductivity, λ the latent heat of evaporation, ΔT the temperature difference between the air and the droplet.

It will be more convenient to write these equations in dimensionless forms :

$$\frac{du_p^*}{dx^*} = - N_2 \frac{c_D}{D_p^* u_p^*} \left| u_p^* - \frac{1}{1+x^*} \right| \left(u_p^* - \frac{1}{1+x^*} \right) \tag{6.50}$$

with

$$c_D = c_D(Re)$$

$$Re = N_1 D^* \left| u_p^* - \frac{1}{1+x^*} \right|$$

$$\frac{dD_p^*}{dx^*} = \frac{- N_3 (2 + 0.6 Pr^{1/3} Re^{1/2})}{D_p^* u_p^*} \tag{6.51}$$

where the dimensionless variables are defined by:

$$D_p^* = D_p / D_{po}$$

$$u_p^* = u_p / u_o$$

$$x^* = x / x_o$$

and the dimensionless groups by:

$$N_1 = D_{po} u_o / \nu_a$$

$$N_2 = 0.75 \rho_a x_c / \rho_p D_{po}$$

$$N_3 = 2 k_a \Delta T x_c / \rho_p \lambda u_o D_{po}^2$$

The initial conditions of this set of equations are:

$$D_p^* = 1 \quad \text{at} \quad x^* = 0 \tag{6.52}$$

and either

$$u_p^* = 1 \tag{6.53}$$

or

$$u_p^* = 0 \qquad \text{at } x^* = 0 \tag{6.54}$$

Equation 53 would hold for pressure nozzles, while equation 54 would hold for pneumatic nozzles with external mixing. Pneumatic nozzles with internal mixing present an intermediate behaviour.

The solution to this set of equations was carried out numerically using a fourth-order Runge-Kutta procedure for the air-water system and with the range:

$$N_1 = 10 \text{ to } 10^4$$

$$N_2 = 0.01 \text{ to } 1$$

$$N_3 \to 0 \quad (\simeq 10^{-6})$$

which covers the ranges encountered in a real spray. The reason for the small value of N_3 (the driving-force number) is that, in the region near the nozzle, air entrainment into the jet is limited and the air quickly approaches saturation.

The results are plotted as $\overline{Nu}$ against N_1 (which is proportional to the air velocity), with N_2 (which is inversely proportional to the droplet diameter) as a parameter, where $\overline{Nu}$ is the average Nusselt number between $x^* = 0$ and $x^* = 50$, an arbitrarily chosen value (figure 4).

It can be seen that $\overline{Nu}$ tends to 2 at low N_1 (low air velocity) and tends to vary as $N_1^{\frac{1}{2}}$ as N_1 becomes large. This can be seen intuitively as follows: from the Ranz-Marshall equation,

$$Nu = 2 + a\, u_R^{\frac{1}{2}} \tag{6.55}$$

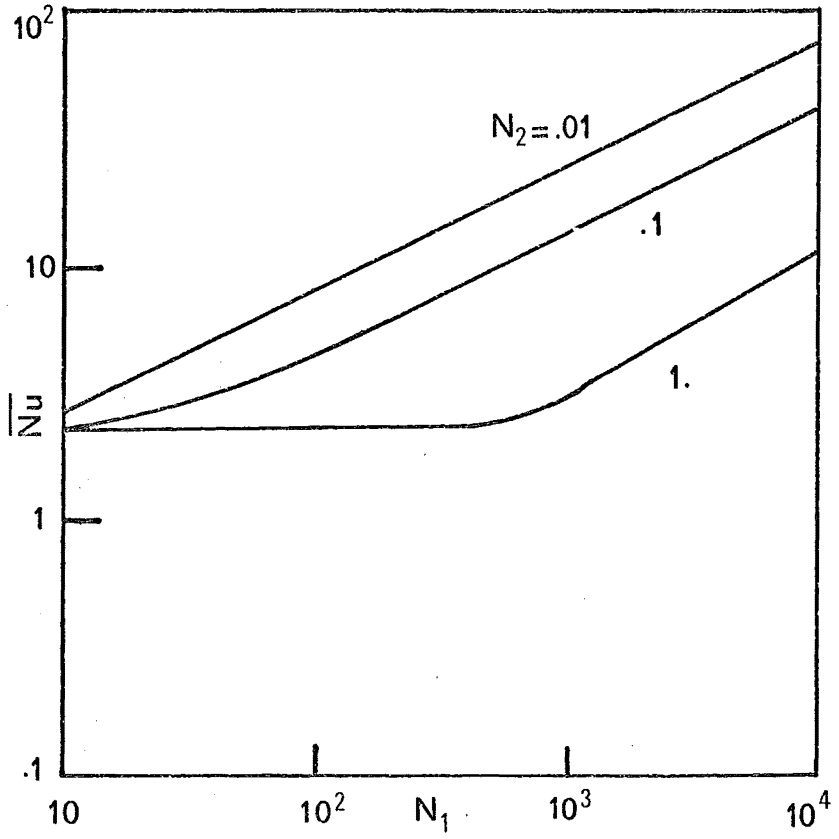
where u_R is the relative velocity. For a given particle size u_R can be expected to vary as u_a.

Hence

$$Nu \simeq 2 + b u_a^{\frac{1}{2}}$$

$$\simeq 2 + c N_1^{\frac{1}{2}} \tag{6.56}$$

The spatial (per unit distance) heat-transfer rate, on the other hand, is also proportional to the time spent in an interval of distance, hence it is inversely proportional to the particle velocity, and approximately inversely proportional to the air velocity.



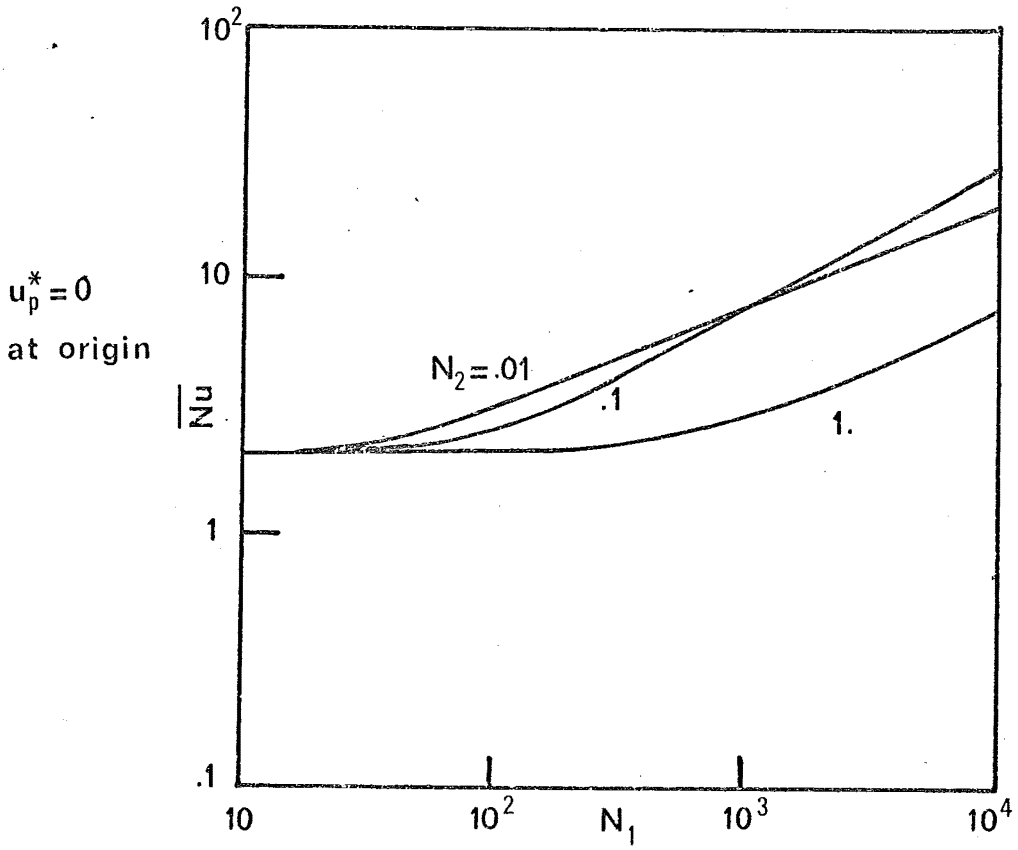


FIGURE 6.4: MEAN NUSSELT NUMBER OF PARTICLE IN DECELERATING AIR FLOW

Hence

$$\text{Spatial transfer rate} \propto \frac{Nu}{u_p} = \frac{2}{u_a} + \frac{d}{u_a^{\frac{1}{2}}} \qquad (6.57)$$

This result will be useful for averaging the jet profile.

II.1.1.4 The averaging of the jet profile

A spray issuing from a nozzle consists of a spectrum of droplet sizes, velocities and directions. Subsequently the droplets will be randomly distributed across the jet and be subjected to different air velocities, temperatures and vapour concentrations. The paths of the particles will contain a random element due to the turbulence of the air. Furthermore, interaction between the jet and the droplets (in the process of heat, mass and momentum transfers) must also be taken into account. Therefore it is impossible to solve the spray evaporation problem by following up each particle rigorously, and even Monte Carlo methods are impractible, due to the great number of variables involved. The approach followed instead will be:

(1) To replace the bell-shaped velocity, temperature and concentration profiles at each point x by "equivalent" flat profiles.

(2) To solve the equations of motion and evaporation for each droplet size, basing on these equivalent profiles.

By means of such an averaging procedure, the problem becomes one-dimensional and manageable. The "equivalent" profiles are those which will give the same spatial rate of evaporation as the real profiles. Since

$$\text{Spatial rate of transfer} \propto (Nu/u_p)\ \Delta T$$

the equivalent velocity profile must give the first term (Nu/u_p) and the equivalent temperature profile the second term.

(a) Equivalent velocity profile

Let $c(\xi)$ be the droplet concentration, where $\xi = r/R_j$ (in the notation of figure 3).

Let $Nu/u_p = f(u_a)$ (6.58)

The equivalent velocity must give rise to the same average (Nu/u_p):

$$\int_o^1 (c\ u_p) \cdot f(u_a) \cdot (\pi\xi d\xi) = f(u_{ae}) \int_o^1 (c\ u_p)(\pi\xi d\xi) \qquad (6.59)$$

where u_{ae} is the equivalent (air) velocity, $(c\ u_p)$ is the flux of particles and $(\pi\xi d\xi)$ the element of area.

u_p may be assumed to have a similar profile to u_a :

$$u_p = u_{pm}(1 - \xi^{1.5})^2 \qquad (6.60)$$

Also, from equation 34,

$$c = c_m(1 - \xi^{1.5})$$

Substituting these back into equation 59, one gets:

$$\int_o^1 (1 - \xi^{1.5})^3\ \xi\ f(u_a)\ d\xi = f(u_{ae}) \int_o^1 (1 - \xi^{1.5})^3\ \xi d\xi \qquad (6.61)$$

From the previous section (equation 57), one has:

$$\frac{Nu}{u_p} = f(u_a) = \frac{a}{u_a} + \frac{b}{u_a^{1/2}}$$

Substituting this into equation 61 and also using equation 27 for u_a, one finally obtains:

$$\frac{a}{u_m} \int_o^1 (1 - \xi^{1.5})\ \xi d\xi + \frac{b}{u_m^{1/2}} \int_o^1 (1 - \xi^{1.5})^2\ \xi d\xi = \left(\frac{a}{u_{ae}} + \frac{b}{u_{ae}^{1/2}}\right) \int_o^1 (1-\xi^{1.5})^3\ \xi d\xi$$

or

$$0.214 \frac{a}{u_m} + 0.129 \frac{b}{u_m^{\frac{1}{2}}} = 0.089 \left(\frac{a}{u_{ae}} + \frac{b}{u_{ae}^{\frac{1}{2}}} \right) \tag{6.62}$$

If the first term on each side of equation 62 is dominant, then:

$$u_{ae} = 0.42\ u_m \tag{6.63}$$

If the second term is dominant,

$$u_{ae} = 0.48\ u_m \tag{6.64}$$

Since the difference is slight, we shall take

$$u_{ae} \simeq 0.45\ u_m \tag{6.65}$$

(b) Equivalent temperature profile

By similar reasoning:

$$\int_0^1 (c\ u_p)\ \Delta T\ (\pi \xi d\xi) = \Delta T_e \int_0^1 (c u_p)\ (\pi \xi d\xi)$$

which, on inserting

$$\Delta T = (T_m - T_\infty)\ (1 - \xi^{1.5}) - (T_p - T_\infty)$$

(from equation 32)

$$c = c_m (1 - \xi^{1.5}) \tag{6.34}$$

and

$$u_p = u_{pm}\ (1 - \xi^{1.5})^2 \tag{6.60}$$

gives:

$$(T_e - T_\infty) = 0.75\ (T_m - T_\infty) \tag{6.67}$$

In summary, we have replaced the real jet by an equivalent jet with the following flat radial profiles:

Air velocity is given by equation 65,

Temperature is given by equation 67,

and in those equation, u_m and T_m, the axis velocity and temperature, can be calculated according to the formulae laid out in section II.1.1.2.

II.1.2 The basic equations of heat and momentum transfer for a single droplet

(a) The equation of evaporation

From equation (5.13a) of Chapter 5, it has been established that:

$$\frac{dE}{dt} = \frac{6(2 + .6\ Re^{1/2}Pr^{1/3})\ D_p k_a \Delta T}{\lambda\ w_{\ell o} \rho_{po}\ D_{po}^3} \tag{6.68}$$

where λ is the latent heat of evaporation, $w_{\ell o}$ the initial liquid mass fraction and ρ_{po} the initial mean droplet density.

When there are differential velocities between the particles themselves and between the particles and the air, it is easier to keep track of the spray as a whole and to set up heat and mass balances if we use the rate of change with respect to distance rather than time. From

$$d/dt = u_{pi} d/dx$$

we finally have

$$\frac{dE}{dx} = \frac{6(2 + .6\ Re^{1/2}Pr^{1/3})\ D_p\ k_a\ \Delta T}{\lambda\ w_{\ell o}\ \rho_{po}\ D_{po}^3\ u_{pi}} \tag{6.69}$$

where u_{pi} is the particle velocity in the x-direction.

(b) The equation of motion

$$m \frac{du_{pi}}{dt} = \frac{1}{2} c_D \left(\frac{\pi D_p^2}{4} \right) \rho_a |\underline{u}_p - \underline{u}_a| (u_{pi} - u_{ai}) + g_i \tag{6.70}$$

where g_i is the acceleration of gravity in the x-direction (axial direction), u_{pi} and u_{ai} the particle and air velocities in the same direction, and c_D is the drag coefficient.

This can be rewritten as:

$$\frac{d(u_{pi}^2)}{dx} = -\frac{1.5\, c_D \rho_a \,|\underline{u}_p - \underline{u}_a|\,(u_{pi} - u_{ai})}{\rho_p\, D_{po}} + 2g_i \qquad (6.71)$$

where ρ_p is the particle density.

Equations 69 and 71 are the two basic equations of the simulation program.

II.1.3 Miscellaneous effects

The methods used in accounting for various influences on droplet behaviour have already been examined in Chapter 5 and will only be briefly recounted here, except for the initial evaporation at the nozzle exit which will be considered in some detail.

II.1.3.1 Effect of mass flux on heat transfer:

Equation 5.24 of Chapter 5 will be used.

II.1.3.2 Effect of radiation:

Either of two methods can be used:

(a) Mean cloud absorptivity method, using equations 5.48,42,46 & 29 of Chapter 5.

(b) Net leaving-flux method, using equation 5.28 of Chapter 5.

II.1.3.3 Turbulence effect:

Turbulence causes a turbulent relative velocity u_R' calculable by equation 5.59 of Chapter 5. This turbulent relative velocity will be added vectorially to the mean relative velocity when calculating the Reynolds number for the drag coefficient and the Nusselt number.

II.1.3.4 Presence of solids

The first effect of solids is to reduce the vapour pressure of the evaporating liquid. For computational purpose the relative reduction will be assumed to be constant throughout the evaporation process and can be found experimentally or calculated from Raoult's or Wüllner's law, assuming a saturated solution.

The second effect is crust formation: each droplet is assumed to shrink freely until a solid crust forms at a certain moisture content. Thereafter the diameter is assumed to be constant. Shrivelling, ballooning and explosions will be ignored.

The third effect of solids is to impede the moisture transfer rate to the surface, by the formation of a membrane or a crust. Let

$$f_d \equiv \frac{\text{drying rate of particle}}{\text{drying rate of liquid droplet of evaporating solution.}}$$

The surface temperature T_s of the particle will be raised according to:

$$T_a - T_s = f_d(T_a - T_s^*) \tag{6.72}$$

where T_s^* is the adiabatic saturation temperature of the evaporating solution.

In general, f_d is a function of the present moisture content, the initial moisture content, the particle diameter and the mean rate of drying in the past history of the particle (these factors all affect the moisture profile in the particle), and the nature of the solid material.

II.1.3.5 Droplet sensible heat:

Some of the heat transferred to the particle must be used to raise or lower the particle temperature. As the heat capacity of the droplet is low compared with its latent heat of evaporation, sensible

heat effects will be neglected except in the case of feed overheat.

The effect of the particle temperature T_p being higher than the adiabatic saturation temperature T_s^* is to multiply the evaporation rate (based on T_s^*) by a factor given in equation 5.63 of Chapter 5. Due to the extra evaporation which takes heat from the particle, its temperature falls at a rate given by equation 5.66 or 5.69 of Chapter 5. Once T_p has fallen to T_s^*, sensible-heat effects can be neglected.

II.1.3.6 Initial evaporation due to atomising air

In pneumatic atomising, due to the intense mixing at the nozzle orifice, the feed and the atomising air will come to hygrothermal equilibrium upon emerging from the nozzle, and some immediate evaporation will take place.

From figure 5 we can write the mass balance for the amount evaporated:

$$G(y_s^* - y_a) = L\, w_{\ell o} E \tag{6.73}$$

and the heat balance:

Dry air enthalpy in + vapour enthalpy in
+ feed enthalpy in
= Dry air enthalpy out + vapour enthalpy out
+ feed enthalpy out .

Assuming that the change in vapour enthalpy is due only to the heat of evaporation of the evaporated vapour, that is, neglecting the sensible heat of the vapour, the heat balance comes to:

$$Gc_{pa}T_a + Lc_{pf}T_f = Gc_{pa}T_s^* + L(1-w_{\ell o}E)c_{pf}T_s + Lw_{\ell o}E\lambda \tag{6.74}$$

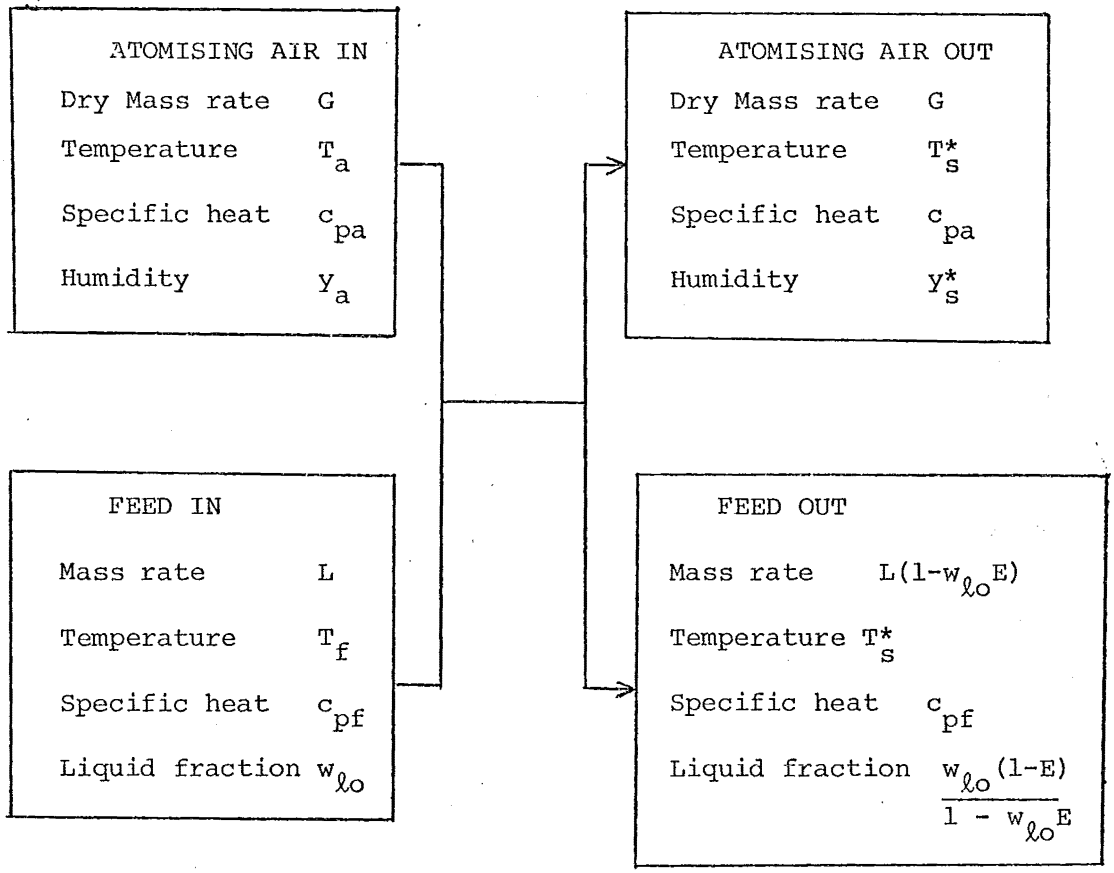
Combining the mass and heat balances we get:

$$T_s^* = T' - K(y_s^* - y_a) \tag{6.75}$$

where $T' = (Gc_{pa}T_a + Lc_{pf}T_f)/(Gc_{pa} + Lc_{pf})$ is the equilibrium temperature in the absence of evaporation, and

Figure 6.5

Mass and heat balance for evaporation at the pneumatic nozzle exit



L include solid and liquid flows.

$$K = G\lambda/(Gc_{pa} + Lc_{pf})$$

is the change in the mean temperature of the air-feed system for a unit change in air moisture due to evaporation.

y_s^* and T_s^* being coupled by the saturation curve, equation 75 can be solved by iteration.

II.1.4 Miscallaneous equations

II.1.4.1 The standard drag curve

The following segmentwise approximation is used:

$$c_D = \frac{24}{Re} \qquad , \quad Re \leqslant .4$$

$$= \frac{24}{Re}(1 + .1\,Re) \qquad , \quad .4 < Re \leqslant 2$$

$$= \frac{24}{Re}(1 + .15\,Re^{.687}) + \frac{.42}{1 + 4.25\times10^{4}\,Re^{+1.16}}$$

$$Re > 2 \qquad (6.76)$$

The last equation is due to Schiller and Naumann and modified by Clift and Gauvin [C5].

II.1.4.2 The saturation curve of water and the calculation of adiabatic-saturation conditions.

The saturation curve of water is calculated by a curve-fitted Riedel-Miller-Planck equation [R6]

$$\ln p_w = \frac{-6348.8}{T} + 22.536 - 0.019639\,T + 1.301\times10^{-5}\,T^2 \qquad (6.77)$$

for T = 300 - 380 K

where p_w is the partial pressure of water measured in atmospheres.

The adiabatic-saturation temperature and humidity are calculated by the Newton-Ralphson iterative method from the equation

$$\frac{y_s^* - y_a}{T_s^* - T_a} = -\frac{c_{ps}}{\lambda} \tag{6.78}$$

where c_{ps} is the wet air specific heat and λ the latent heat of evaporation, and

$$y_s^* = \frac{0.622\ p_w}{1 - p_w} \tag{6.79}$$

II.1.4.3 Droplet size distribution

Nukiyama-Tasanawa's equation (eqn. 19) with $\delta = 0.5$ is recommended:

$$\mathcal{G} = aD_p^{\,2} \exp(-bD_p^{\,0.5}) \tag{6.80}$$

where

$$b = \sqrt{\frac{\Gamma(12)}{\Gamma(10)\bar{D}_{vs}}} \tag{6.81}$$

$\mathcal{G}$ is the number of droplets between D_p and $D_p + dD_p$, and Γ is the gamma function. A maximum diameter (2.5 to 3 $\bar{D}_{vs}$) must be specified.

II.1.4.4 Terminal velocity calculations

Where necessary, the terminal drag c_{Dt} of a particle is calculated by:

$$c_{Dt} = \frac{576}{\Pi} \quad , \ \Pi \leqslant 10 \qquad \text{(Stokes regime)} \tag{6.82}$$

$$= \frac{574}{\Pi} + \frac{32}{\Pi^{.39}} + \frac{1}{1.8 + 758\Pi^{-.36}} \ , \ \pi > 10 \tag{6.83}$$

(Smith's equation [S12])

where

$$\Pi = c_{Dt}\, Re_t^2 = \frac{4\rho_p g D_p^3}{\rho_a \nu_a^2}$$

in which g is the gravitational acceleration, ν_a the air kinematic viscosity, D_p the particle diameter, ρ_a and ρ_p the air and particle densities respectively.

II.1.4.5 Air properties

The air density will be assumed to be inversely proportional to the absolute temperature.

The viscosity of the air, μ_a , is calculable by the modified Sutherland equation[K5]:

$$\mu_a = \frac{1.488 \times 10^{-6}\, T^{1.5}}{T + 122.1 \exp(-11.5/T)} \quad , \qquad (6.84)$$

$$90K < T < 1845K$$

where T is the absolute temperature in degree K.

The thermal conductivity of air, k_a , is given by Keyes' equation[G3]:

$$k_a = \frac{2.646 \times 10^{-3}\, T^{1.5}}{T + 245 \exp(-27.6/T)} \quad , \qquad (6.85)$$

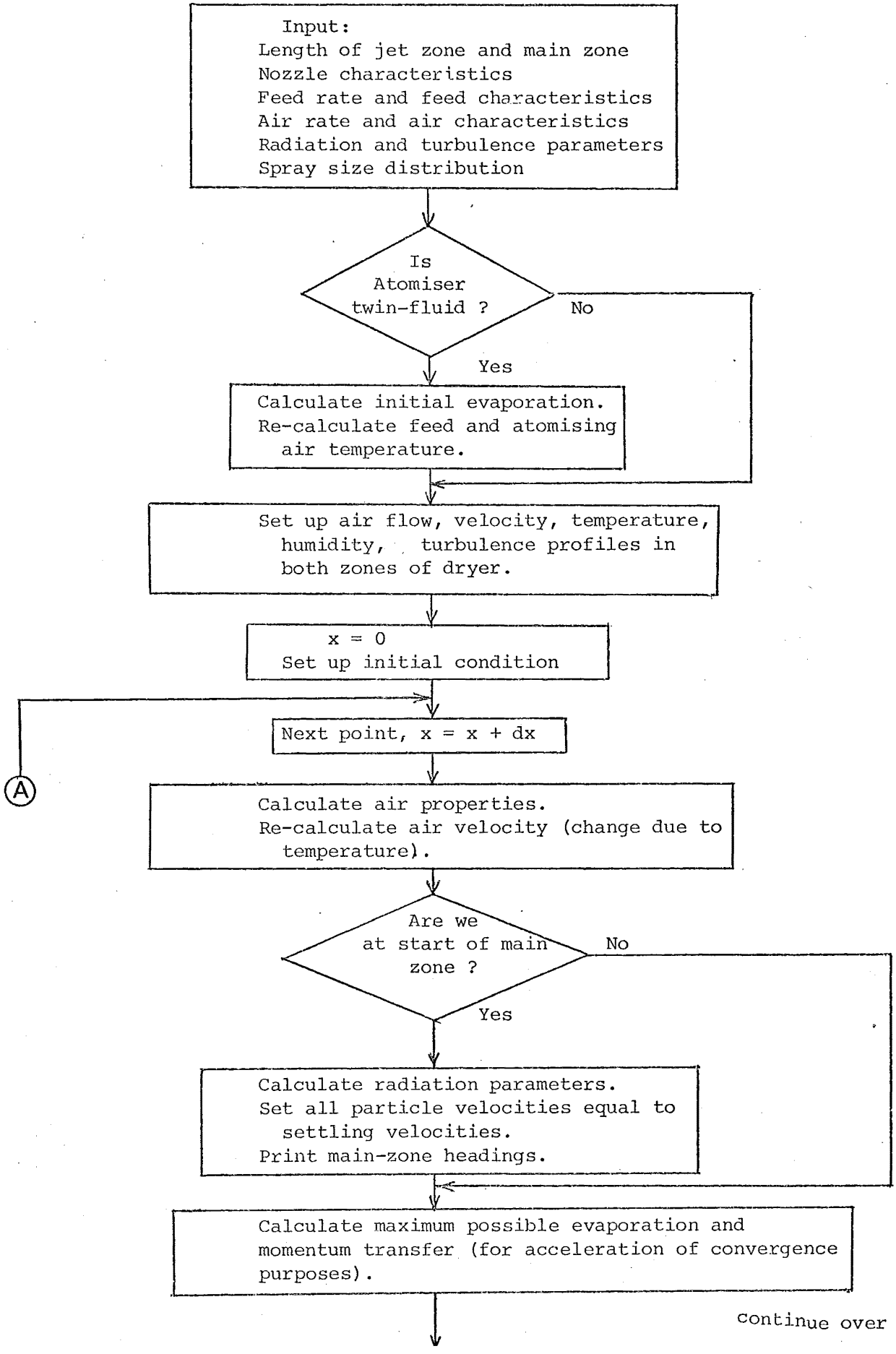
$$90K < T < 584K$$

II.2 Computational problems

A simplified flow chart for the calculation has been drawn in figure 2. A more detailed version is now given in figure 6. The actual program written in Fortran can be found in Appendix D.

Since the air properties (density, viscosity, thermal conductivity) and the adiabatic saturation conditions change fairly slowly, their values can be based on the previous point in space. Similar

Figure 6.6 DETAILED FLOW DIAGRAM OF SIMULATION OF COCURRENT SPRAY DRYER.



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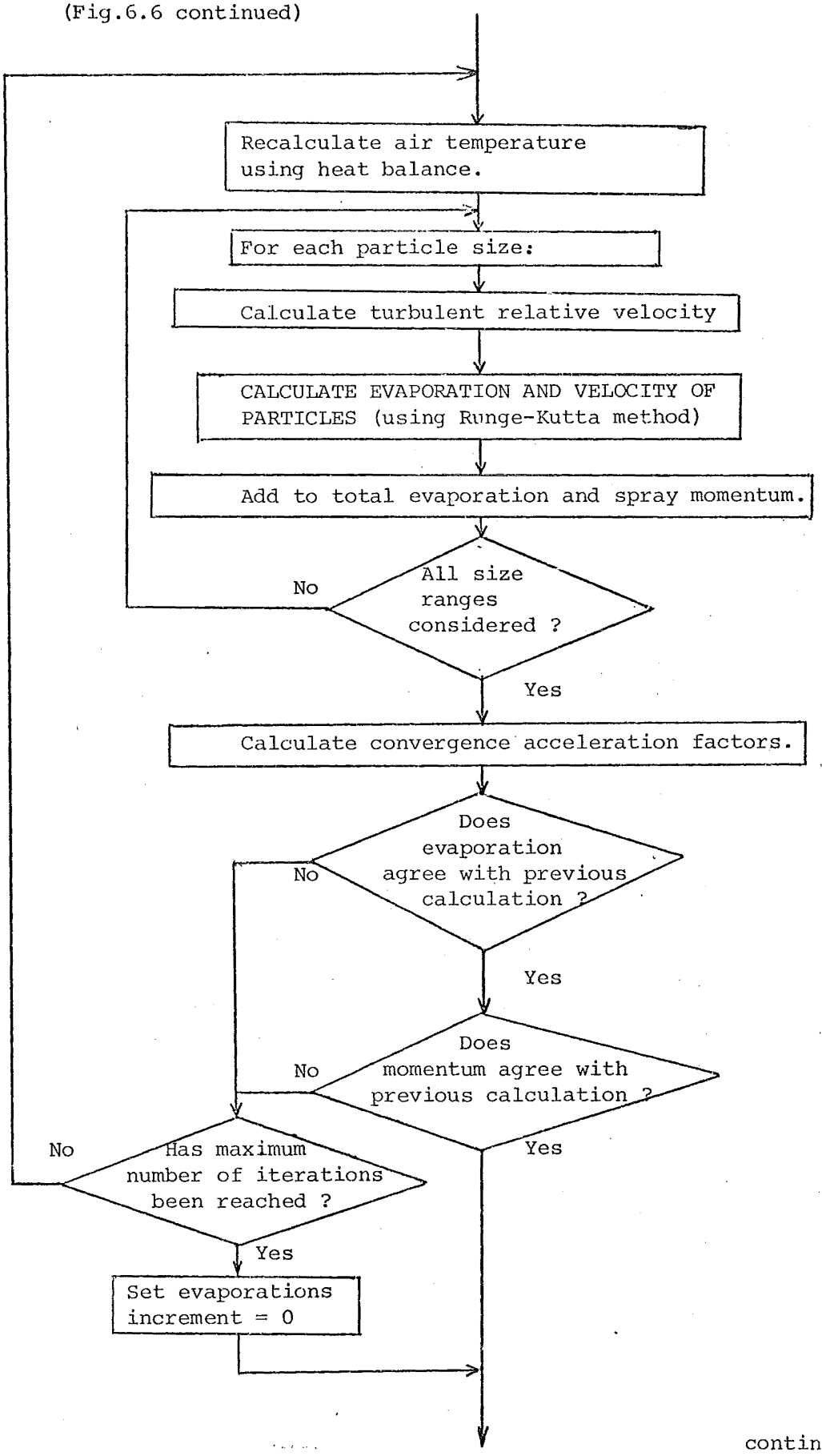
(Fig.6.6 continued)



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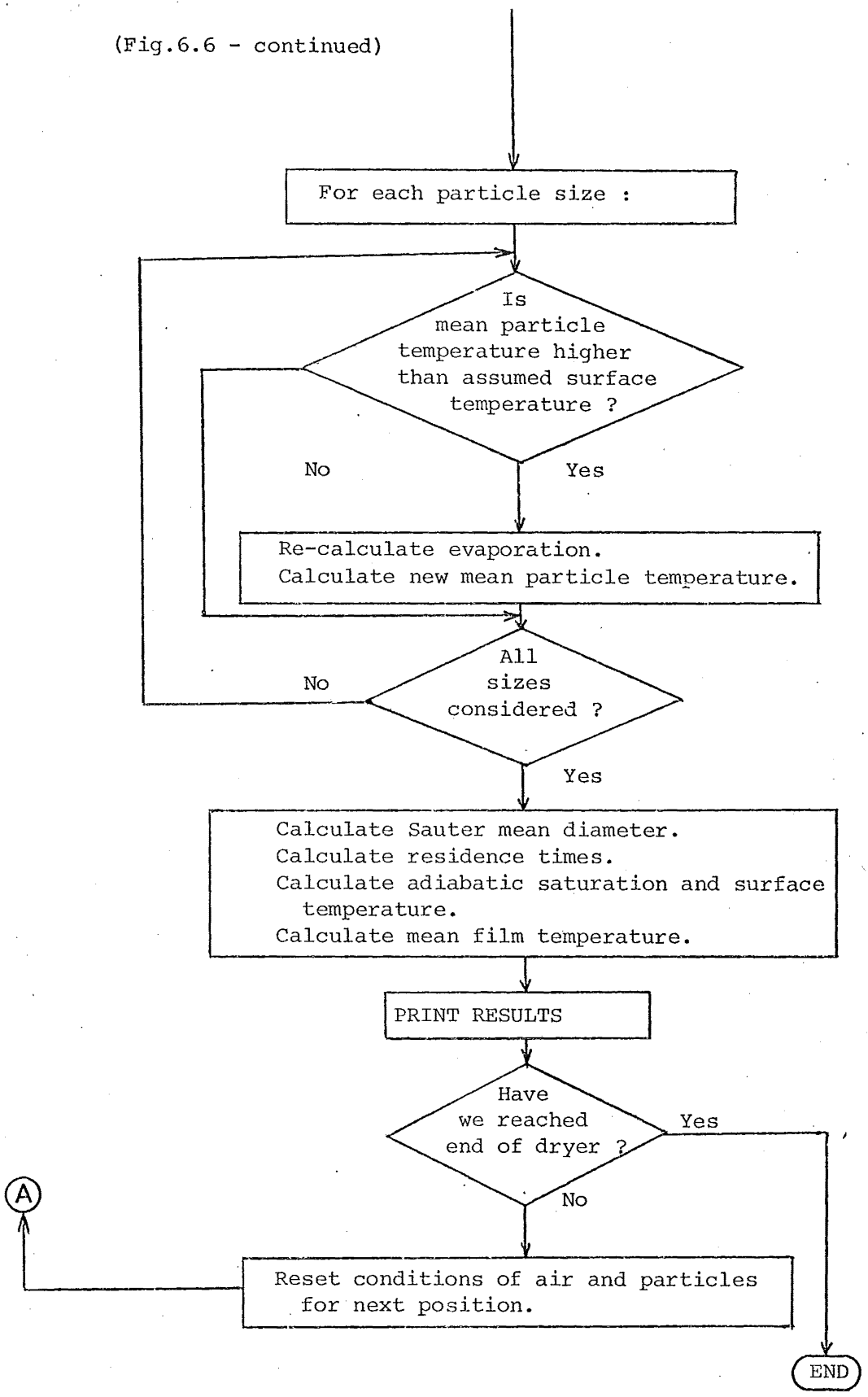
(Fig.6.6 - continued)



conditions apply for the droplet surface temperature and relative turbulent motion. As a distance increment is only a few thousandths of the total dryer length, this approximation will not involve large errors.

In the jet zone, a major problem is the convergence of the iteration procedure used in recalculating air conditions and hence evaporation. The problem arises from the high transfer coefficient (due to high relative velocities), rapid change in the air velocity and temperature profiles, and small air flow rate. A small amount of evaporation will cause a major change in air temperature and humidity, hence the iteration becomes easily unstable and must be somehow accelerated. The procedure is outlined in figure 7.

The purpose is to make the new estimate of the fraction evaporated, $E^{(2)}$, a certain combination of the previous two estimates $E^{(0)}$ and $E^{(1)}$, which would be as close to the correct value E_i as possible. Suppose this has been done and $E^{(2)} = E_i$.

Consider $(E_m - E^{(0)})$ to be a measure of the driving force used in the previous calculation, and $(E_m - E_i)$ to be the "real" driving force. Since the increase in evaporation between the last position and this one is roughly proportional to the driving force, one can write:

$$\frac{\text{Previous estimate of increase in evaporation}}{\text{Previous estimate of driving force}} = \frac{\text{real increase in evaporation}}{\text{real driving force}}$$

$$\frac{E^{(1)} - E_{i-1}}{E_m - E^{(0)}} = \frac{E_i - E_{i-1}}{E_m - E_i} \tag{6.86}$$

or

$$E^{(2)} \simeq E_i = \frac{E^{(1)} E_m - E^{(0)} E_{i-1}}{E_m - E_{i-1} + E^{(1)} - E^{(0)}} \tag{6.87}$$

Figure 6.7

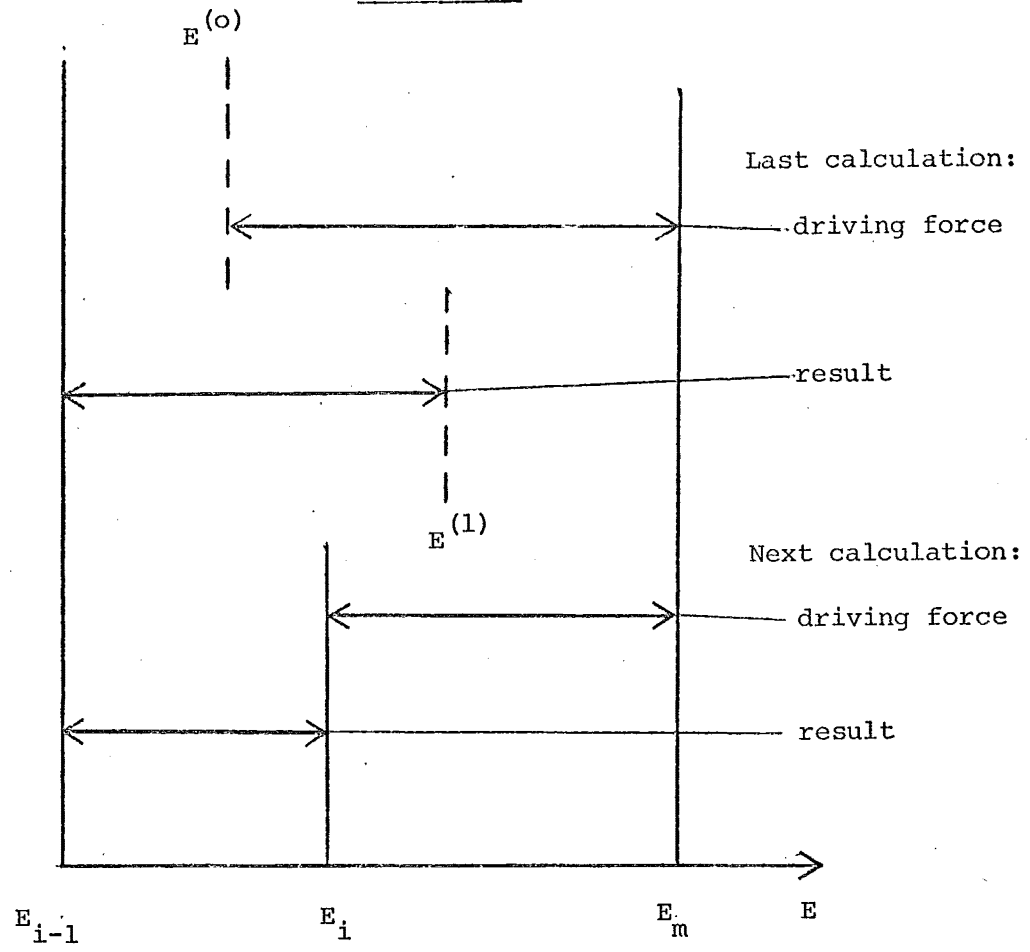


Fig.6.7 Illustration of convergence acceleration scheme for evaporation calculation.

E_{i-1} = evaporation at previous position

E_i = correct value of evaporation at present position

E_m = maximum possible evaporation at present position based on the available air flow

$E^{(o)}$ = a first estimate of E_i

$E^{(1)}$ = a second estimate of E_i, based on air conditions which result from $E^{(o)}$.

which is the combination that we are seeking. A similar equation can be found for momentum transfer.

II.3 Sample calculations and results

The simulation program was applied to two cases with quite different characteristics: a very fine spray ($\bar{D}_{vs}$ = 12 μm) of pure water in a jet-dominated air flow, and a coarse spray ($\bar{D}_{vs}$ = 105 μm) of milk in a spray dryer with only a short jet zone. The results will be compared with experimental data available.

II.3.1 Evaporation of a fine, pure water spray in a jet zone

II.3.1.1 Operating conditions

Manning and Gauvin [M3] presented evaporation, temperature, droplet sizes and droplet velocity data in their cocurrent tall-form spray dryer. The air inlet is designed to minimise turbulence and backmixing, and thus it can be assumed that the jet zone extends through the whole zone considered (which is 0.5 m long). This assumption was checked by doing a numercial computation of droplet velocities based on jet-zone characteristics (section II.1.1). The predicted pattern of deceleration agrees satisfactorily with experimental measurements (figure 8).

Manning and Gauvin's run 29 was used for our sample calculation as the data for this run were complete. The input conditions given by them (or calculated from their specifications) are summarised in Table 2. It must be noted that for a pneumatic nozzle with an annular outer air outlet, the outer radius of the air annulus must be used as the "orifice radius", r_o, mentioned in jet theory.

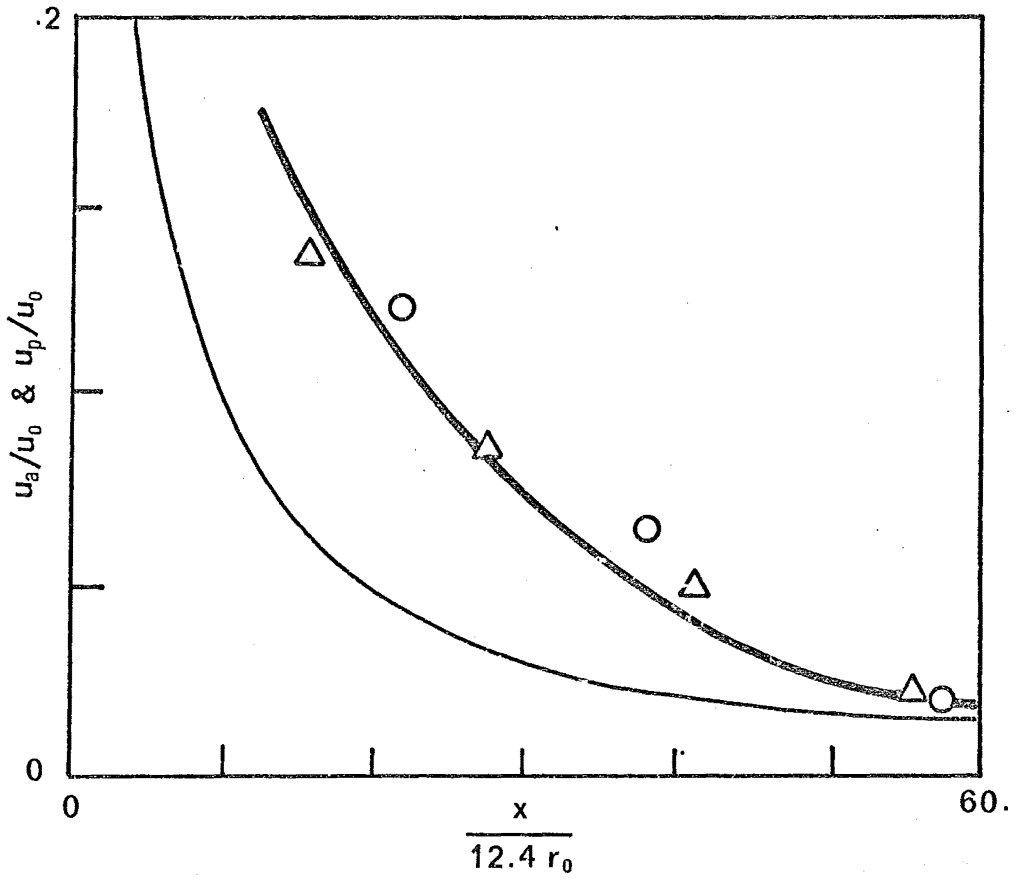


FIGURE 6.8: VELOCITY OF A 40μm DROPLET IN THE JET ZONE OF A PNEUMATIC NOZZLE (JN12)

——— Predicted air velocity

▬▬▬ Predicted droplet velocity

△ Data (M3) at 173 kPa g. atomising pressure

○ Data (M3) at 242 kPa g. – –

TABLE 6.2

Input conditions for sample calculation 1

(pure water, fine spray)

Flow pattern: cocurrent with jet zone characteristics.

Nozzle type: pneumatic with internal mixing (Spraying Systems Co. type JN 12)

Air orifice radius = 7.6×10^{-4} m.

Nozzle operating conditions:

Atomising air rate = 9.1×10^{-4} kg/s

Atomising air orifice velocity = 370 m/s

Atomising air temperature = 300 K

Liquid rate = 5.55×10^{-4} kg/s

Liquid temperature = 300 K

Spray half angle = 12.4 deg.

Feed properties: (pure water)

Density = 1×10^{3} kg/m^{3}

Latent heat of evaporation = 2.46×10^{6} J/kg

Specific heat = 4.19×10^{3} J/kg K

Solid mass fraction = 0.

Drying air:

Flow rate = 3.8×10^{-2} kg/s

Inlet temperature = 377 K

Inlet humidity = .005 - .01 kg/kg

Turbulence = negligible

Spray size distribution:

Nukiyama-Tasanawa, with dispersion parameter

$\delta = 0.5$ and

$\bar{D}_{vs} = 12$ μm

II.3.1.2 Results and discussion

The results are plotted in figure 9 together with experimental data.

Agreement is quite good except for $\bar{D}_{vs}$, which increases more slowly than was observed. This may be due to the inaccuracy of the size distribution assumed, and also possibly to some inaccuracy in the droplet sampling procedure. The authors used a collection cell method for measuring droplet diameters. If some smaller droplets were not collected, due to their low inertia, and the effect insufficiently accounted for, then the Sauter diameter measured would be higher than the actual value.

In figure 10 is plotted the calculated evaporation when the jet zone stops and the main zone starts at points A, B, C. It can be seen that evaporation in the jet zone is by comparison severely limited, due to the high droplet velocities (hence low residence time) and limited air available. The graph shows the severe errors that would be involved if the jet dynamics were not accounted for.

In figure 11a the air velocity at the orifice is reduced by 33% . Increased residence times give rise to increased evaporation, but the latter increase is slight (3 to 10%), justifying our assumption in averaging equations 63 and 64 for the equivalent velocity. In practice this increase in evaporation will be almost exactly balanced by a decrease due to the reduction in air entrainment (figure 11a). On the other hand, changes in nozzle operating conditions will affect the drop sizes[K6], which will have a very large effect on the performance (figure 11b).

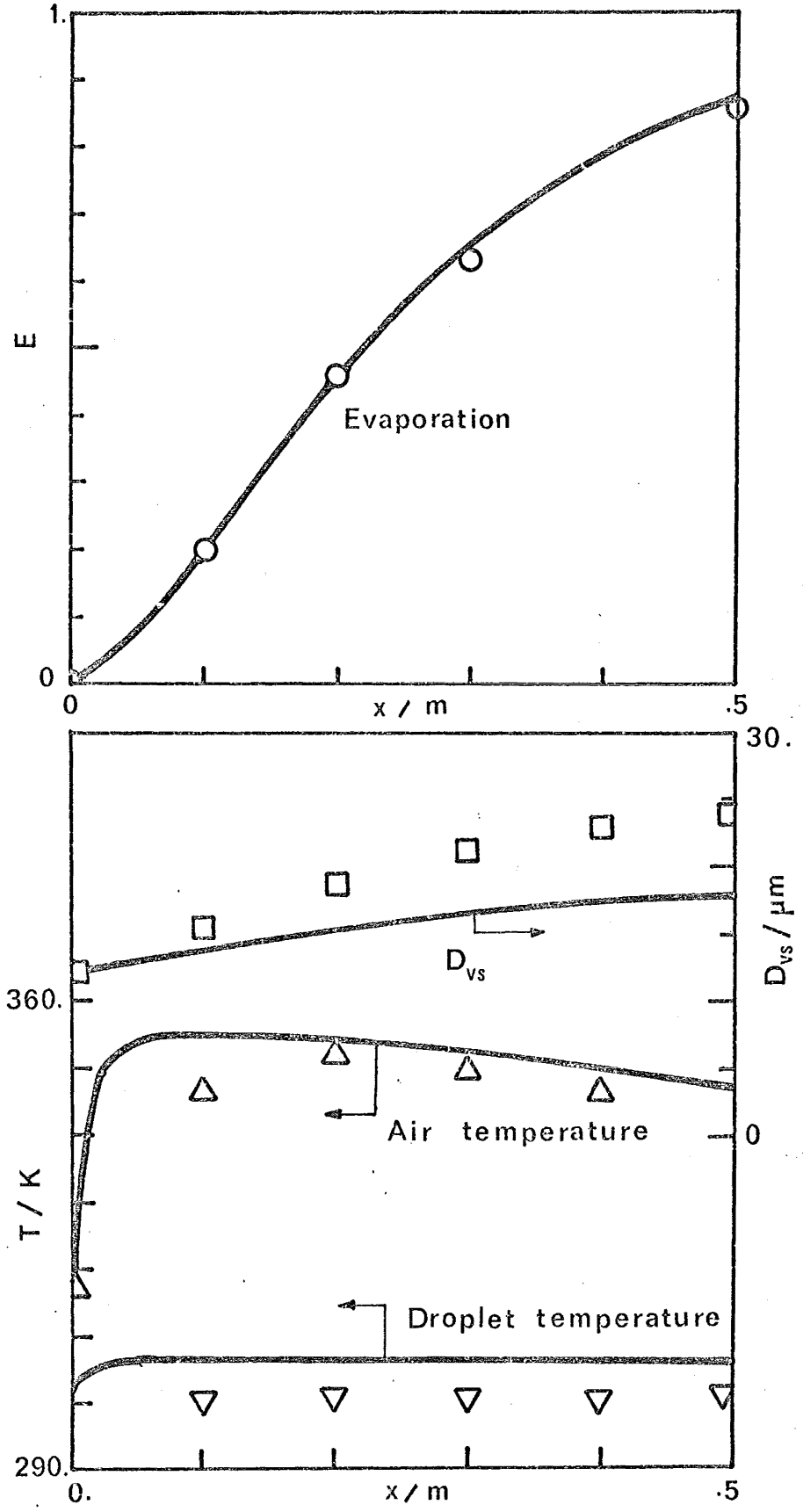


FIGURE 6.9 : JET - ZONE EVAPORATION , WATER SPRAY

○ □ △ ▽ Data (M3)

——— Calculation

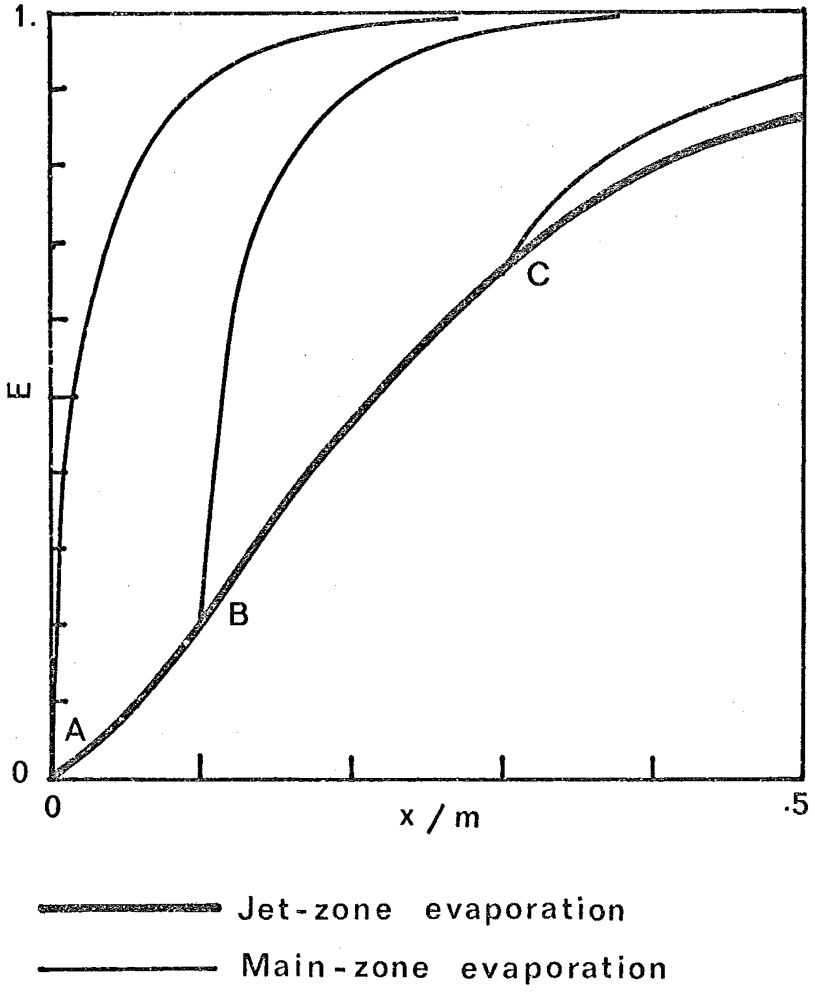


FIGURE 6.10 : COMPARISON OF JET- & MAIN-ZONE EVAPORATION

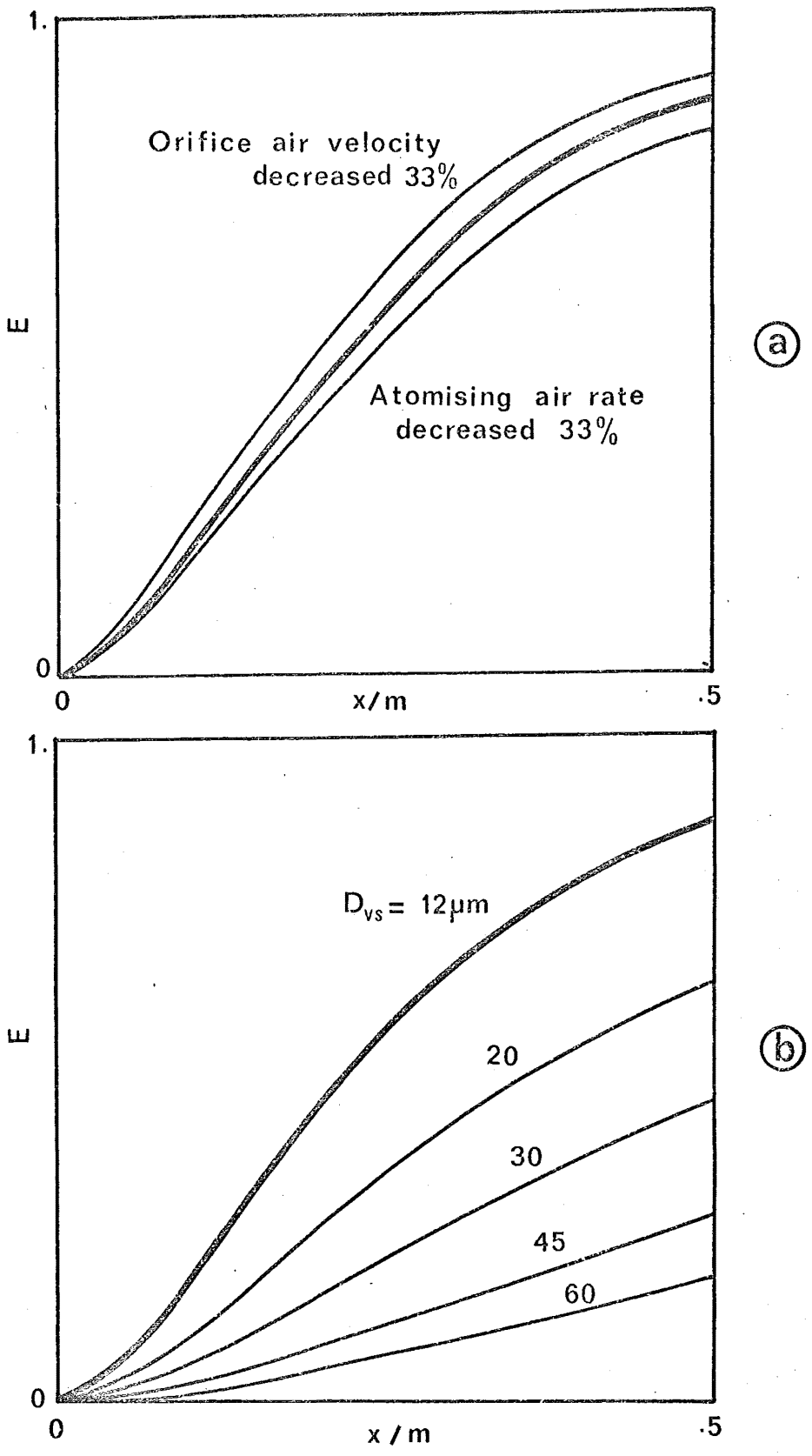


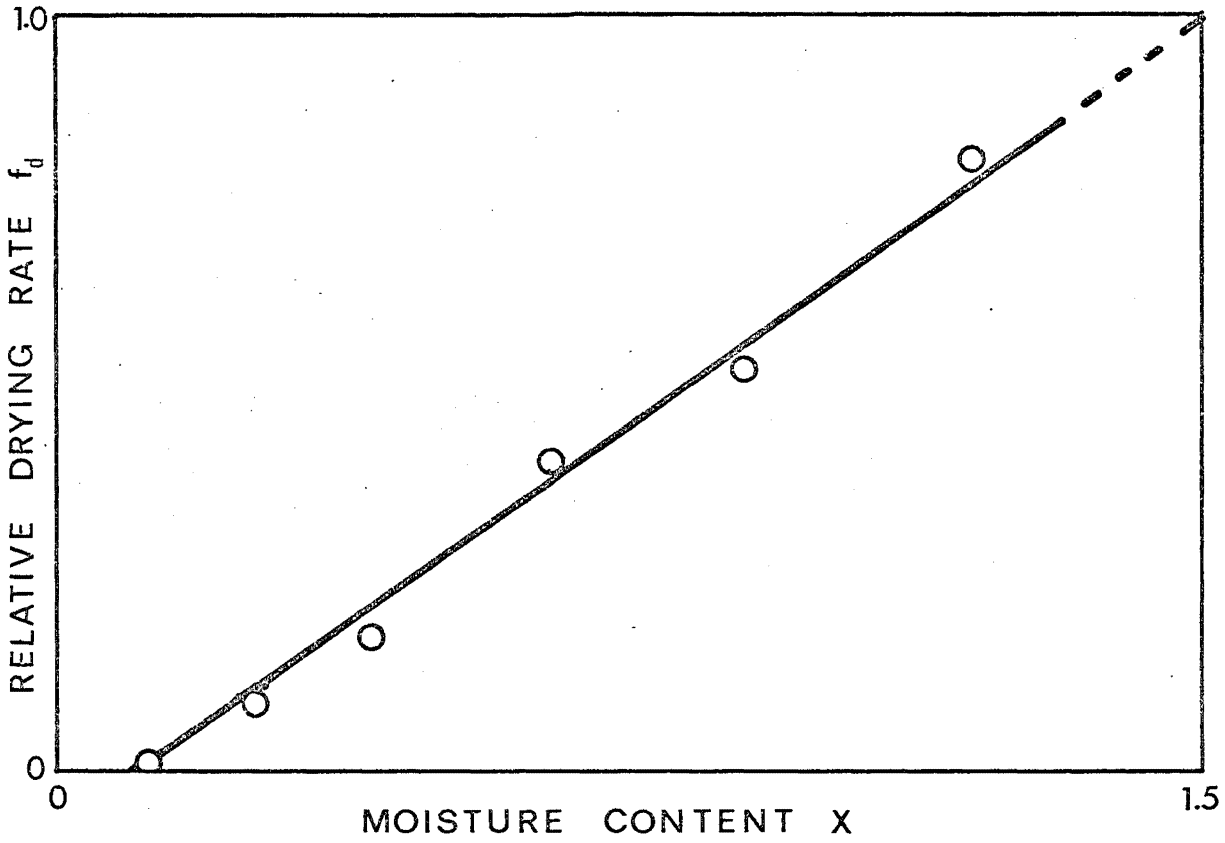
FIGURE 6.11 : EFFECT OF ATOMISING CONDITIONS ON JET-ZONE EVAPORATION

II.3.2 Evaporation of a coarse spray of skim-milk in a predominantly main zone dryer.

II.3.2.1 Operating conditions

The data used in this calculation are based mainly on a skim-milk spray dryer studied by Hayashi[H5], with the difference that his drying chamber is squat (length/diameter ratio = 1) and has nozzles on the wall, while this calculation will assume a purely cocurrent situation. Hayashi's dryer is 8 m tall. It was found that his droplet size distribution data can be fitted very well with the Nukiyama-Tasanawa equation,80. Further properties of skim-milk and skim-milk powder were taken from Hall and Hendrick[H1], King[K7, K8], Webb and Johnson[W1] and Masters[M8]. All the quantities used are typical values in the dairy industry. The inputs are summarised in Table 3.

The drying curve of milk droplets was found from the supported drop data of Trommelen and Crosby[T7] who plotted drop surface temperature T_s and fractional evaporation E against time. From their data the relative drying rate (compared with unhindered evaporation), f_d, can be found by using equation 72. Trommelen and Crosby's results are re-plotted in figure 12 as a drying curve (f_d vs X) in which X is the dry basis moisture content. The result is an almost linear falling rate curve starting from the moment drying begins, i.e. even before the crust forms. This conclusion is supported by the work of Campbell-Board[C1] who, in similar experiments with reconstituted condensed skim-milk, was unable to find a constant-rate period. A probable explanation for this surprising phenomenon is the early formation of a flexible membrane on the surface of the droplet, which hinders moisture transfer but does not prevent shrinking.



Data from ref. T7 for initial X = 1.5

FIGURE 6.12 : DRYING CURVE FOR SUSPENDED DROP OF MILK

TABLE 6.3

Input conditions for sample calculation 2

(spray of skim milk)

Air flow pattern: cocurrent, with jet zone from 0 - .5 m, transition with linear gradients from .5 - 1 m, main zone 1 - 10 m.

Nozzle type: pressure nozzle
Orifice radius = 4×10^{-4} m

Nozzle operating conditions: Jet half-angle = 38 deg.
Feed rate = 0.02 kg/s
Feed temperature = 350 K.

Feed properties:

Solid mass fraction = 0.50

Solid density = 1590 kg/m^3

Liquid density = 1000 kg/m^3

Latent heat of vaporisation = 2.46×10^6 J/kg

Feed specific heat = 3950 J/kg K

Liquid mass fraction at solidification = 0.178

Drying curve = linear throughout evaporation

Lowering of vapour pressure due to solutes: negligible according to Raoult's law

Drying air flow:

Flow rate = 0.6 kg/s

Inlet velocity = 2.4 m/s

Inlet temperature = 400 K

Inlet humidity = 0.005 kg/kg

Mean turbulent velocity (assumed) = 0.02 m/s

Mean Lagrangian scale of turbulence (assumed) = 0.001 s

Radiation parameter:

Tower diameter = 2 m

Projected particle area/unit volume = 0.3 m^2/m^3

Particle absorptivity = 1

Stainless steel wall emissivity = .85

Mean wall radiating temperature = 370 K.

Spray size distribution:

Nukiyama-Tasanawa distribution with parameters

$\delta = 0.5$

$\bar{D}_{vs} = 105$ μm

II.3.2.2 Results and discussion

The fraction unevaporated F = 1-E is plotted against distance in figure 13.

(a) Comparison with available data:

The calculation gives at 8 m a product unbound moisture content of 1.7%. To this must be added the hygroscopic moisture about 1% at this temperature and humidity (H1), hence the total product moisture is 2.7% which is in reasonable agreement with Hayashi's value of 3.1% for his 8 m chamber.

The outlet air temperature is 362 K which is also in the recommended range (Hayashi's value is 364 K).

However, the calculation assumed a uniform amount of shrinking for all droplet sizes, hence $\bar{D}_{vs}$ is larger for the feed than for the product:

$$\bar{D}_{vs} \text{ (feed)} = 105 \ \mu m$$

$$\bar{D}_{vs} \text{(product)} = 84 \ \mu m$$

Literature data give the same value of $\bar{D}_{vs}$ for feed and product, indicating that some puffing has taken place, probably in the lower size range since the specific evaporation in these sizes is most rapid. If that is true, then the overall accuracy of the calculation will not be affected, as will be shown later.

(b) Shape of the F-curve and influence of the drying curve of single droplets:

Again it can be seen that the jet zone severely restricts evaporation. From about 5 m the (ℓnF) curve becomes linear with x. The reason is that all droplets are now almost completely evaporated except the largest ones, which comprise about 30% of the total mass and a much smaller percentage of the total number (table 5). These lie in a fairly narrow size range, have consolidated and fall with constant velocity.

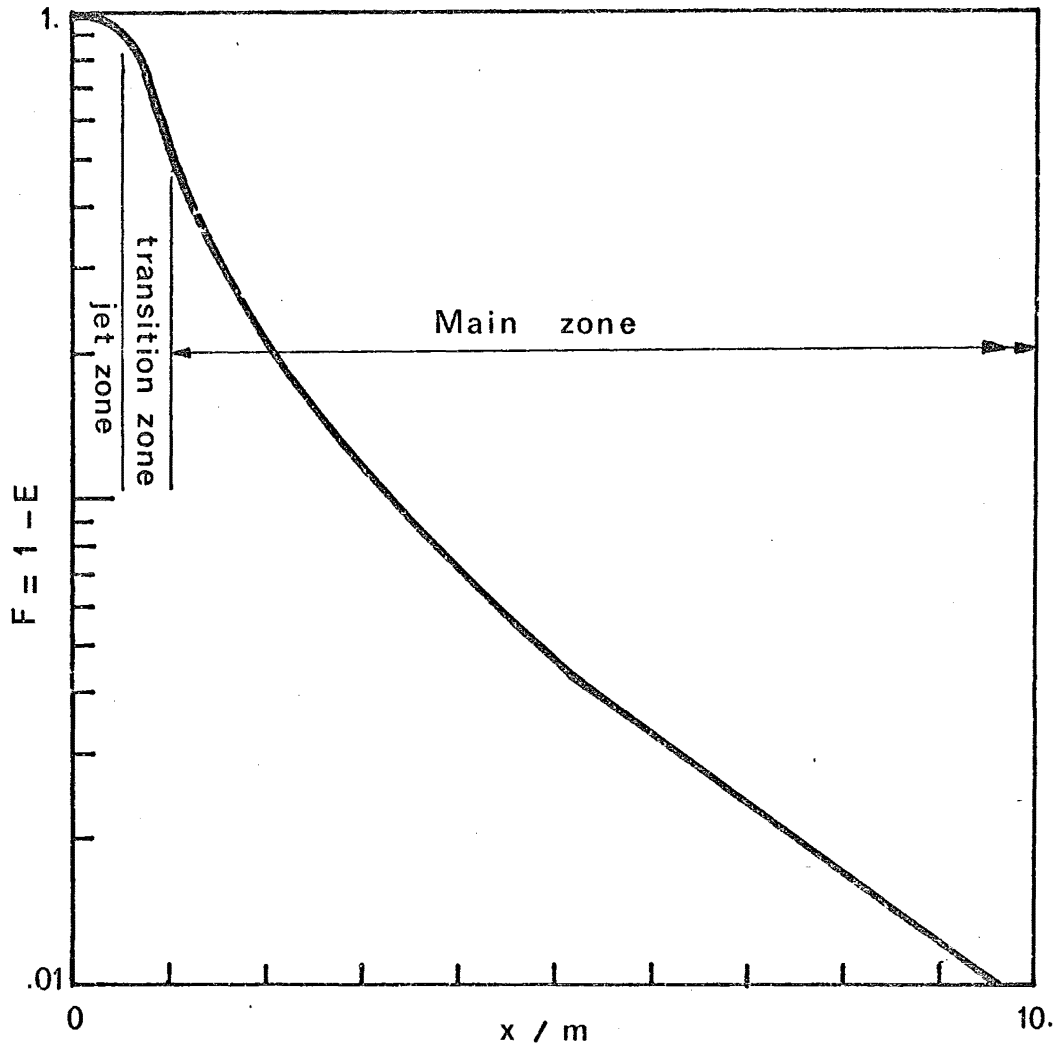


FIGURE 6.13: EVAPORATION CALCULATION FOR SKIMMILK

The linearity of the ℓnF vs x graph is due to our earlier assumption of a linear falling rate, which makes the evaporation process a first-order reaction, provided the diameters are constant (equation 4). Thus the importance of getting an accurate single-droplet drying curve is emphasized.

(c) Importance of the maximum droplet size

The largest droplets are the governing factor in the design and performance of spray dryers. In one calculation in this work, the finest size ranges, up to 130 μm and making up 50% of the spray original mass, are assumed to evaporate completely upon entering the main zone. The drying curves of the larger sizes were found to be almost unaffected by this and, as a result, from the 4 m level downwards the total evaporation curve is almost the same as for a "correct" calculation (Table 4).

TABLE 4

Effect of small droplet evaporation on large droplet behaviour

Initial sizes / μm	Fractional evaporation at 4 m	
	Correct calculation	Finer ranges immediately evaporated
0 - 130	1.000	1.000
150 - 170	.959	.957
190 - 210	.843	.838
230 - 250	.713	.708
270 - 290	.598	.594

This suggests that if one wants to avoid a tedious size-by-size calculation, one can simply consider the largest drop size and ignore the rest, an approach followed by Gluckert[G9], Gauvin and Katta[G6,K1] and others. However such an approach is justified only if we want a fully dried product. For incompletely dried products the droplets below the maximum size will still have some importance (Table 5).

(d) Sensitivity analysis

The calculation of the milk spray was repeated with variations in each of the main parameters. The effect of turbulence is found to be negligible in this particular case. This is not surprising since the main air velocity is low, and the particles being rather large have high settling velocities (up to .9 m/s), hence Re, c_D and Nu are little affected by the turbulent relative velocity.

The effect of radiation is also negligible, the reason being that, in milk spray drying, fairly low temperatures are involved.

The strongest influences are those of the drying air rate and inlet air temperature, and the solid content of the feed. These and other effects are plotted in figure 14. It must be kept in mind that the altering of any one operating condition will result in the change of several variables, the effects of which must be added together. For example, if the air temperature is increased, air velocity, wall temperature, heat loss ... will also be changed.

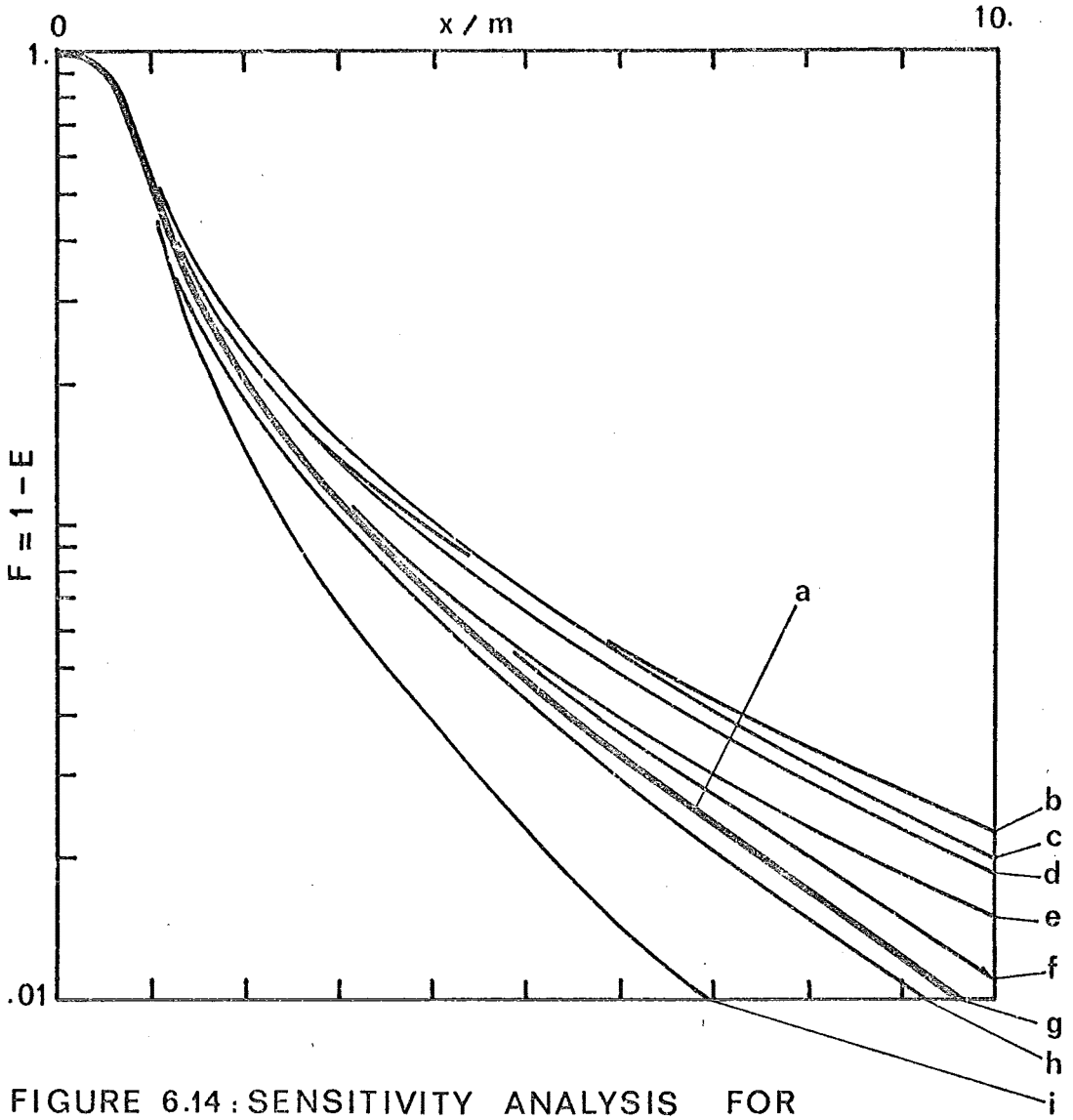


FIGURE 6.14 : SENSITIVITY ANALYSIS FOR SKIMMILK EVAPORATION

(a) Original operating conditions.

(b) Air flow rate decreased 15%

(c) Sauter diameter increased 15%

(d) Solid mass fraction decreased 20%

(e) 2 K/m air temperature gradient caused by heat loss

(f) Feed temperature decreased by 40 K

(g) Turbulence neglected. Also radiation neglected. Also, feed ejection velocity increased 50%.

(h) Inlet air velocity decreased 15%

(i) Inlet air temperature increased by 30 K.

III. INFLUENCE OF RESIDENCE TIME DISTRIBUTION ON EVAPORATION

Most calculation methods, including the simulation in the previous sections, assume a perfectly cocurrent or countercurrent air-spray system. In real spray dryers, deviations from plug-flow for each phase will tend to modify the performance, often in a disfavourable direction.

III.1 Influence of air residence time distribution

Using the residence time distribution (R.T.D.) data of the air, one can model the flow pattern in the drying chamber, and hence get a realistic picture of the temperature, velocity and humidity profiles. For example, if the RTD data point to the existence of a well-mixed (stirred tank) zone in the dryer, then the profiles of the air conditions in this zone must be assumed to be uniform instead of varying steadily as in the case of perfect plug flow.

Obviously this cannot be done in a first calculation, as the extent of evaporation and its influence on the air are not yet known. Thus a suggested procedure is:

(1) Calculate the evaporation based on perfect plug-flow for each phase.

(2) Modify the air condition profiles according to the evaporation calculated and the actual flow pattern.

(3) Recalculate the evaporation.

(4) Repeat steps 2 and 3 if necessary.

Apart from the effect on evaporation, an equally serious consequence of air deviations from plug-flow, especially in cocurrent dryers, is that backmixing may bring hot air into contact with dry particles to damage the product if it is heat sensitive. If sufficiently

accurate information on the drying curve of the material is available, this effect can be studied by calculating the droplet or particle temperature at each point. However, random fluctuations in real systems may make this impossible.

It must also be noted that a model based on RTD data only is not guaranteed to be exact. Its validity will depend on how much is known of the geometry and general behaviour of the system, and it is always desirable to back up the results with other data, such as visualisation or velocity measurements (Chapter 3).

III.2 Influence of spray R.T.D.

III.2.1 General approach

Dispersed-phase R.T.D. data are difficult to obtain and very little work has been done in this field. But theoretically it is easy to predict its influence on evaporation. This is because the dispersed phase is a macromixed system (Chapter 2), that is, its droplets or particles do not remerge and resplit during their travel through the chamber, but remain separate entities. Whereas with micromixed systems the performance depends on the actual flow pattern and the same RTD can give rise to quite different yields (except for first order reactions), the conversion of a macrofluid depends on the RTD only[L6]:

$$F_L = \int_0^\infty \left(\frac{c_A(t)}{c_{Ao}} \right)_{plug} C(t)dt = \int_0^\infty F(t)\, C(t)dt \qquad (6.88)$$

where F_L is the fraction unconverted at the outlet, $C(t)$ the RTD or impulse-response curve, and $F(t) = [c_A(t)/c_{Ao}]_{plug}$ is the fraction unconverted as a function of residence time in a plug flow (or batch) reactor, which can be calculated readily.

In a spray system the situation is further complicated by the fact that different droplet sizes have different R.T.D.s. Thus, in a rigorous calculation, the fraction unconverted f_j of each size range must be found separately, then added:

$$F_L = \sum_{j-1}^{N} \int_o^\infty f_j(t)\ C_j(t)dt = \int_{oo}^{\infty\infty} f_j(D_{po},t)\ C(D_{po},t)dt\ dD_{po} \qquad (6.89)$$

where the index j=1,2...N refers to the j-th size range. Both f_j and C now are functions of initial size as well as of time.

This general equation can be tedious to apply, but in general the smaller droplet sizes can be ignored as they are completely evaporated long before approaching the outlet, as has been shown earlier.

III.2.2 Geometrically similar R.T.D. curves for all sizes

An interesting case is when the R.T.D. curves of all sizes are similar in shape and have the same amount of relative dispersion, that is, when the ratio of the second moment σ_t and the first moment $\bar{t}(D_{po})$ are the same:

$$\left[\frac{\sigma_t}{\bar{t}(D_{po})}\right]_j = \text{constant for all sizes} \qquad (6.90)$$

or

$$C_j\left(D_{po}, \frac{t}{\bar{t}(D_{po})}\right) = C_j(D_{po}, \Theta) = C(\Theta)\ , \qquad (6.91)$$

all sizes.

For example, all sizes may display dispersed plug-flow behaviour with the same Peclet number.

Equation 89 then can be written as:

$$F_L = \int_0^\infty \left\{ \int_0^\infty f_j(D_{po}, \bar{t}(D_{po}).\theta) d\, D_{po} \right\} C(\theta)\, d\theta \qquad (6.92)$$

where $\theta = t/\bar{t}(D_{po})$ and $\bar{t}(D_{po})$ is the mean residence time of particles with initial diameter D_{po}.

Further assuming that the mean velocity $\bar{u}_p(D_{po})$ of each size is constant through the length L of the dryer,

i.e.

$$\bar{u}_p(D_{po}) = \frac{L}{\bar{t}(D_{po})} \qquad (6.93)$$

then

$$\theta = \frac{t}{\bar{t}(D_{po})} = \frac{t\, \bar{u}_p(D_{po})}{L} = \frac{x}{L} \qquad (6.94)$$

i.e. θ in equation 92 is both the relative residence time and the relative distance moved through the dryer. The usefulness of this result is that $f_j(\theta)$ can now be readily calculated with a simulation. Equation 92 becomes:

$$F_L = \int_0^\infty \left[\int_0^\infty f_j(D_{po}, \frac{x}{L}) dD_{po} \right] C(\theta) d\theta \qquad (6.95)$$

The term in brackets is simply the conversion of the spray as a whole at the relative position x/L, which is F(x/L).

Hence

$$F_L = \int_0^\infty F(\theta)\, C(\theta)\, d\theta \qquad (6.96)$$

where $\theta = x/L$ for F

$= t/\bar{t}$ for C

Equation 96 is similar in form to equation 88 except for the independent variable. In this equation no inte gration over droplet sizes is necessary. $F(\theta) = F(x/L)$ is assumed to have been calculated in a simulation or other computation, and $C(\theta) = C(t/\bar{t})$ is the impulse response curve or RTD curve for any particular size (equation 91).

III.2.3 First-order reaction assumption

If the evaporation process can be assumed to be of first order, i.e.

$$-\frac{dF}{dx} = k_1'' F \tag{6.97}$$

or

$$-\frac{dF}{d\theta} = k_1' F \tag{6.98}$$

then

$$F = F_e \exp(- k_1' \theta) \tag{6.99}$$

and the right-hand side of equation 96 is simply the product of F_e and the transfer function of the spray. In these equations, k_1'' and k_1' have been defined as the specific rate of evaporation with respect to distance rather than time, because when there is relative motion between particles no common time base can be found. Also, in the simulation program, F is calculated as a function of distance.

The first-order reaction assumption can be used in two important cases:

(a) The constant mean-evaporative-diameter case:

This case has been extensively examined in section II.1.2 and no more will be said here.

(b) The linear drying rate case:

The first-order reaction approximation will hold if the following conditions are fulfilled:

(1) The particles are falling at constant velocity;

(2) They have consolidated and stopped shrinking;

(3) They have entered a region in the drying curve where the relative drying rate varies linearly with the moisture content, i.e.

$$-\frac{dF}{dt} = k_1 F \tag{6.100}$$

(4) Evaporation is confined to a narrow size range.

Then it can easily be seen that equations 97, 98 will hold. Although the conditions quoted seem restrictive, they probably often occur in practice, as can be seen from the sample calculation on a milk spray (figures 12, 13, 16 and Table 5).

III.2.4 Extended first-order reaction method

By assuming a first-order reaction, we replaced the exact equation 96

$$F_L = \int_0^\infty F(\theta)\ C(\theta)\ d\theta$$

by the equation

$$F_L = \int_0^\infty F_e \exp(-k_1', \theta).\ C(\theta)\ d\theta \qquad (6.101)$$

so that the error involved is

$$\Delta F_L = \int_0^\infty [F(\theta) - F_e \exp(-k_1' \theta)]\ C(\theta)\ d\theta \qquad (6.102)$$

Usually F_e and k_1' are taken to fit the evaporation curve $F(\theta)$ towards the outlet of the dryer ($\theta \to 1$), where $C(\theta)$ is large. Hopefully the term in brackets in equation 102 is important only at low θ, when $C(\theta)$ in turn becomes small, and thus the error will be small.

When this is not the case, as when $C(\theta)$ has a large dispersion and remains high for small θ, then the accuracy of the calculation can be improved by writing:

$$F(\theta) = F_1 \exp(-k_1' \theta) + F_2 \exp(-k_2' \theta) + \ldots \qquad (6.103)$$

where F_i and k_i' , i = 1 to N, are chosen to give the best fit, especially near $\theta = 1$.

Then equation 101 can be extended to:

$$F_L = \sum_{i=1}^{N} F_i \int_0^\infty \exp(-k_i' \theta)\ C(\theta)\ d\theta \qquad (6.104)$$

which is a weighted sum of transfer functions.

Equation 103 may in fact come up quite often in cocurrent spray drying, one of the terms being due to the mean evaporative diameter remaining approximately constant, and another term being due to the linearity of the final period drying curve (the two cases examined in the last section). The former would be dominant in the early period of drying, while the latter would be dominant in the final period.

For example, the $F(\theta)$ curve for the sample calculation for skim-milk can be very accurately represented in the main zone by:

$$F(\theta) = 0.36 \exp[-1.31(x-1)] + 0.17 \exp[-.33(x-1)] \qquad (6.105)$$

as evidenced by figure 15. Note that in this case the constant M.E.D. assumption does not depend on the assumption of zero relative velocity between the particles, provided the evaporation rate is based on distance rather than time.

III.2.5 Sample calculation of R.T.D. effect

As an example we shall take the spray of milk studied earlier. Data for the calculations are summarised in Table 5 and figure 16, where apart from the R.T.D. characteristics all the information has been obtained from the computer simulation. Equation 105 (figure 15) must also be noted.

From Table 5 it can be seen that evaporation is controlled by size ranges 10 to 14 (D_p = 200-300 μm), which display similar RTD curves (axially dispersed plug flow with a Peclet number of 36), and have a roughly constant velocity in the whole of the dryer main zone (figure 16a). Hence the conditions for equation 96 have been fulfilled.

From figure 16 the particle residence times in the jet and transition zones are very low, so that only the main zone needs to be considered. In equation 96 and subsequent equations we shall take

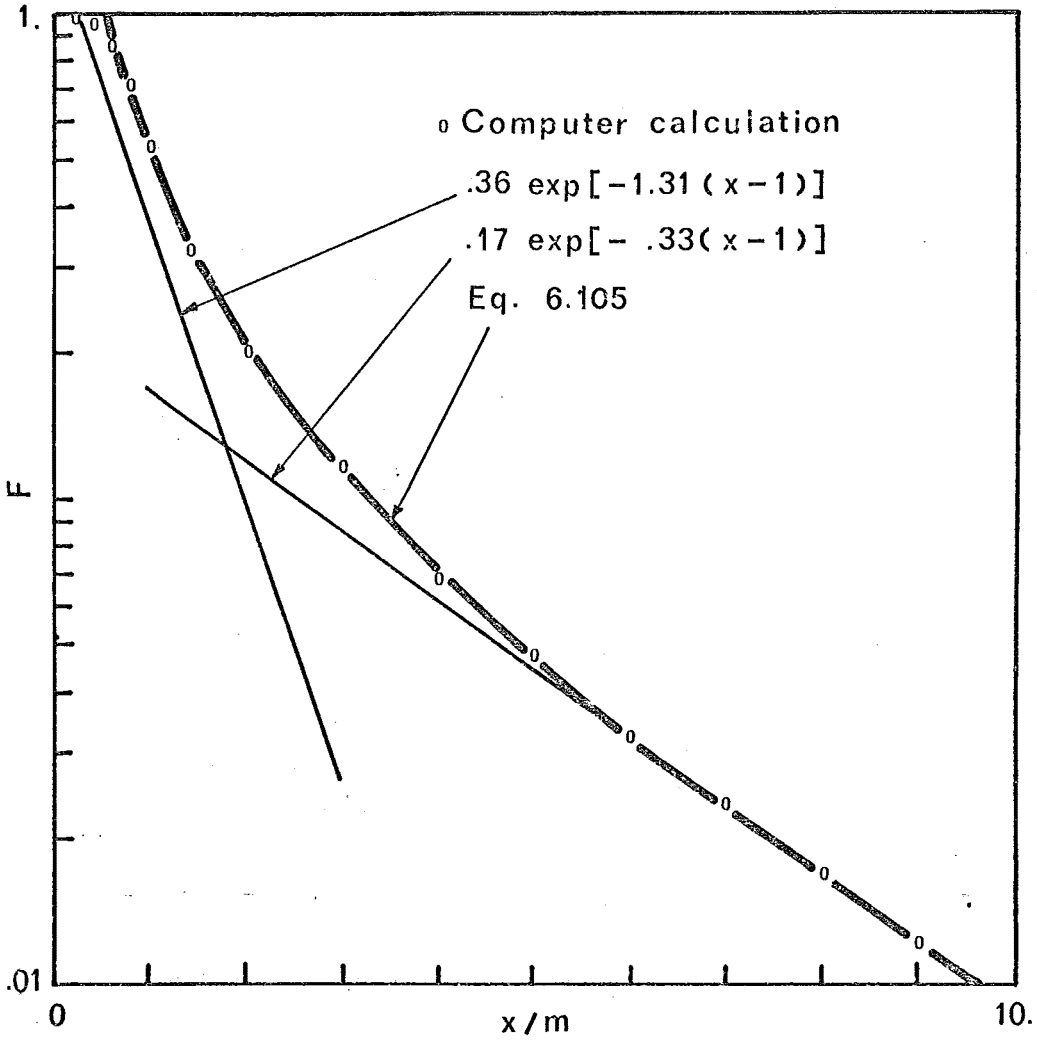
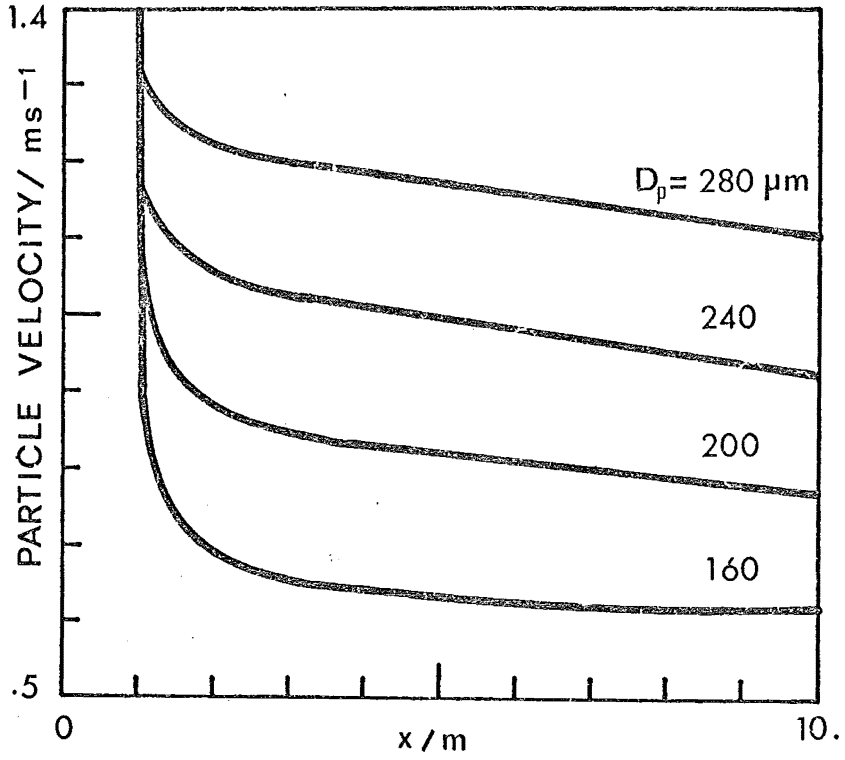


FIGURE 6.15: EVAPORATION OF SKIMMILK SPRAY AS A SUM OF FIRST-ORDER REACTIONS



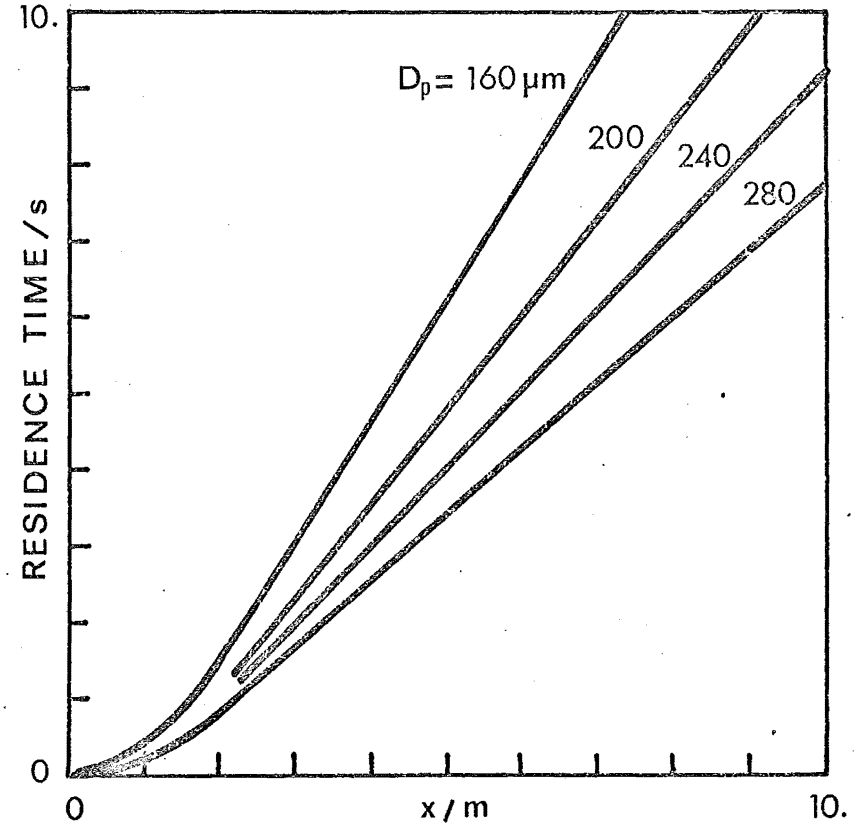


FIGURE 6.16: PARTICLE VELOCITY & RESIDENCE TIME IN SAMPLE CALCULATION

TABLE 6.5

Input conditions for calculation of effect of spray R.T.D. on evaporation of milk

Dryer length: 8 m

Fraction unevaporated at outlet for pure plug-flow: 0.0170

Length of jet zone: 1 m

Spray R.T.D.: Axially dispersed plug-flow for each size group, with Peclet numbers given below.

Size group no.	Diameter /μm	Initial mass fraction of total spray V_j	Fraction unevaporated f_j	$V_j f_j$	Pe
1 - 7	0 - 150	.6083	0	0	-
8	150-170	.0930	0	0	-
9	170-190	.0783	.0016	1.3×10^{-4}	36
10	190-210	.0647	.0077	5.0×10^{-4}	36
11	210-230	.0526	.0215	1.13×10^{-3}	36
12	230-250	.0421	.0446	3.19×10^{-3}	36
13	250-270	.0337	.0757	2.55×10^{-3}	36
14	270-290	.0268	.1127	3.02×10^{-3}	36

θ as the relative distance into the main zone:

$$\theta = \frac{x - L_j}{L_m}$$

where L_j = 1 m is the length of the jet and transition zone, and L_m = 7 m is the length of the main zone.

Because the velocities of the particles are fairly constant, θ is also equal to $t/\bar{t}(D_{po})$ for any size D_{po}, and the impulse response curve in terms of θ for any size is:(L5)

$$C(\theta) = \frac{1}{2}\sqrt{\frac{Pe}{\pi\theta}} \exp\{ - \frac{Pe(1-\theta)^2}{4\theta} \} \qquad (6.106)$$

for which the transfer function is:

$$\mathcal{F}(s) = \exp\left[\frac{Pe}{2}\left(1 - \sqrt{1 + \frac{4s\tau}{Re}}\right)\right] \qquad (6.107)$$

Substituting equations 106 and 107 into 104, we finally obtain for the fraction unevaporated F_L :

$$F_L = .36 \exp\left[\frac{Pe}{2}\left(1 - \sqrt{1 + \frac{4x9.2}{Pe}}\right)\right] + .17 \exp\left[\frac{Pe}{2}\left(1 - \sqrt{1 + \frac{4x2.3}{Pe}}\right)\right]$$

$$= .0005 + .0192$$

$$= .0197$$

as compared with F_L = .0170 for the perfect plug-flow case (figure 13).

IV. CONCLUSION

In this chapter it has been shown that, due to the great number of factors affecting the spray drying process, analytical methods are usually inadequate for predicting the performance of industrial spray

dryers. The suggested procedure is first to do a numerical (stepwise) calculation, assuming perfect plug-flow regime, then correct for residence-time-distribution effects. A computer program was written to carry out the first step for cocurrent systems, but accounting for residence-time-distribution effects is possible only in some cases.

The jet zone near the nozzle and the size of the largest droplets were shown to be important factors in limiting the performance of a dryer. But, above all, because in industrial situations one usually goes far into the falling rate period of the droplets, research into the drying curve of droplets of various materials seems to be of great importance before more accurate predictions can be made.

NOTATION FOR CHAPTER 6

A area, [m^2]

c concentration, [kg/m^3]

$C(t)$ impulse response curve, [s^{-1}]

$C(\theta)$ impulse response curve as function of dimensionless time, [-]

c_D drag coefficient of particle, [-]

c_p specific heat, [J/kg K]

D diameter, [m]

D_e mean evaporative or equivalent diameter, [m]

D_h hydraulic diameter of vessel = 4 x volume/area, [m]

$\bar{D}_{m,n}$ m-n mean diameter, [m]

D_{vs} 3-2 or Sauter or surface-volume mean diameter, [m]

D_m maximum diameter, [m]

$\mathfrak{D}$ diffusion coefficient, [m^2/s]

$\mathfrak{D}_t$ turbulent dispersion coefficient, [m^2/s]

E fractional evaporation, [-]

F fraction unevaporated (=1-E), or more generally fraction unreacted, [-]

f_c ratio of present to initial specific evaporation rate, [-]

f_d relative drying rate (compared to constant rate period), [-]

f_j fraction unevaporated or unreacted for a particular size group, [-]

$\mathcal{F}(s)$ Transfer function, [-]

G gas flow rate, [kg/s]

g gravitational acceleration, [m/s^2]

$\mathcal{G}$ number size distribution = dn/dD_p, [m^{-1}]

h heat transfer coefficient, [W/Km^2]

j liquid/gas density ratio = ρ_l/ρ_g , [-]

(Notation for Chapter 6, cont.)

k_a air thermal conductivity, [W/mK]

k_1 specific (per unit remaining mass) rate of conversion (or evaporation) = reaction rate constant for first-order reactions, [s^{-1}]

k_1' first-order reaction rate constant or specific rate of conversion, in terms of dimensionless time or distance, [-]

k_1'' first order reaction rate constant or specific rate of conversion (or evaporation) in terms of distance = k_1/velocity, [m^{-1}]

k_e extinction coefficient, or projected particle area per unit particle cloud volume, [m^{-1}]

L liquid or feed flow rate, [kg/s]

L_b mean beam length, [m]

n fraction of total number of particles under size D_p , [-]

p_w water vapour partial pressure in atmosphere.

q heat transfer rate, [W]

q_R heat transfer rate by radiation, [W]

R_j jet radius, [m]

R_s factor to account for feed overheat effect on evaporation, [-]

r radial position, [m]

r_o orifice radius, [m]

$\mathcal{R}$ rate of growth of droplet = dD_p/dt, [m/s]

s Laplace Transform parameter, [s^{-1}]

S shape or view factor in radiation, [-]

T temperature, [K]

T_s surface temperature, [K]

T_s^* adiabatic saturation temperature, [K]

t time, [s]

$\bar{t}$ mean residence time, [s]

t_p particle time constant, [s]

(Notation for Chapter 6, cont.)

u velocity, [m/s]

u_R relative velocity between particle and fluid, [m/s]

u_o orifice velocity of air in pneumatic nozzles, of feed in pressure nozzle, [m/s]

u_a' air turbulent velocity, [m/s]

u_R' turbulent relative velocity, [m/s]

V volume, [m^3]

v volume fraction of particles under a size D_p , [-]

w mass fraction, [-]

X dry basis moisutre content, [-]

x distance from nozzle, [m]

x_1, x_2, x_3 lengths defined in figure 3, [m]

y air humidity, dry basis, [-]

y_s surface humidity, dry basis, [-]

y_s^* adiabatic saturation humidity, dry basis, [-]

α jet half-angle, [degree]

δ dispersion index in size distributions, [-]

λ latent heat of evaporation, [J/kg]

μ_z mean value of variable z.

μ viscosity, [N s/m^2]

ν kinematic viscosity [m^2/s]

ξ dimensionless radial position, [-]

π 3.14159 ...

Π $c_D\ Re^2$, [-]

ρ density, [kg/m^3]

σ_z standard deviation of variable z.

τ time parameter, [s]

θ dimensionless time or distance, [-]

(Notation for Chapter 6, cont.)

Dimensionless Groups:

$B = C_{pm}\Delta T/\lambda$, Spalding number.

N_1 , N_2 , N_3 : as defined on page 214.

$Nu = hD_p/k_a$, Nusselt number.

$Sh = k_c D_p/\mathfrak{D}$, Sherwood number.

$Pr = \nu_a G_a/k_a$, Prandtl number.

$Sc = \nu/\mathfrak{D}$, Schmidt number.

$Pe = uL/\mathfrak{D}_t$, Peclet number.

Subscripts:

a air

c cloud

e equivalent,
equilibrium

f fluid,
feed

g gas

i in the i-th direction

j referring to size group j

ℓ liquid

L at end of chamber

m maximum,
axis value (in a jet),
mixture

p particle or droplet

s solid,
surface

t terminal (velocity)

w wall

o initial (at t = 0 or at x = 0)

∞ at infinite distance, in surrounding

Superscripts:

* equilibrium or saturation

* dimensionless

CONCLUSION

In the second part of this work (Chapters 2, 3, 4) the residence-time distribution approach using transfer-function analysis has been found to be a powerful way of investigating flow patterns, and thus of improving spray-dryer design and operation. The methods and results described may be of more general usefulness in the study of process equipment, especially those concerning the transfer-function analysis, the correlation of droplet entrainment, and mixing phenomena in a vessel with a sudden inlet expansion or with a secondary jet.

The evaporation prediction method described in the third part (Chapters 5 and 6) has been shown to be capable of great flexibility and accuracy. However, it also pointed out the necessity of obtaining more data on the evaporation of single droplets of the materials to be dried, and this would seem to be one of the most useful areas of research for some time to come.

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APPENDIX A

DATA AND RESULTS OF RESIDENCE TIME DISTRIBUTION (R.T.D.) EXPERIMENTS

Contents

Table A1: Input concentration curves for drying and atomising air R.T.D.

AIR RTD INPUT CONCENTRATION CURVE NO. 11
APPLIES TO RUNS 5
TIME= 0.10 SECONDS TO 30.00 SECONDS IN INTERVALS OF 0.10 SECONDS

0	177	469	825	951	989	956	723	590	456	374	291	244	211	192	175	161	149	138	132	126	120	115	110	105
100	96	92	88	85	82	80	77	75	73	71	70	68	67	65	64	63	62	60	59	58	57	56	55	54
53	52	51	50	49	48	48	47	47	46	46	45	45	44	44	43	43	42	42	41	41	40	40	39	39
38	38	37	37	36	36	36	35	35	34	34	34	33	33	32	32	32	31	31	30	30	30	29	29	29
28	28	28	27	27	27	26	26	26	25	25	25	24	24	24	24	23	23	23	22	22	22	22	21	21
21	21	20	20	20	20	19	19	19	19	18	18	18	18	18	17	17	17	17	17	16	16	16	16	16
15	15	15	15	15	14	14	14	14	14	14	13	13	13	13	13	13	12	12	12	12	12	12	12	11
11	11	11	11	11	11	10	10	10	10	10	10	10	10	9	9	9	9	9	9	9	9	9	8	8
8	8	8	8	8	8	8	8	7	7	7	7	7	7	7	7	7	7	7	6	6	6	6	6	6
6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2

TIME= 31.00 SECONDS TO 60.00 SECONDS IN INTERVALS OF 1.00 SECONDS

2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0																				

AIR RTD INPUT CONCENTRATION CURVE NO. 12
APPLIES TO RUNS 9
TIME= 0.05 SECONDS TO 15.00 SECONDS IN INTERVALS OF 0.05 SECONDS

488	696	849	947	990	977	910	788	611	379	326	279	238	203	175	154	138	129	126	130	125	121	116	112	108
103	99	95	90	86	83	79	76	74	71	69	66	64	62	61	59	57	56	54	53	51	50	48	47	46
44	43	42	41	40	39	38	37	36	35	34	33	32	31	31	30	29	28	28	27	27	26	26	25	24
24	23	23	23	22	22	21	21	21	20	20	20	19	19	19	18	18	18	17	17	17	16	16	16	16
16	15	15	15	15	14	14	14	14	14	13	13	13	13	13	13	12	12	12	12	12	12	11	11	11
11	11	11	10	10	10	10	10	10	10	9	9	9	9	9	9	9	9	9	8	8	8	8	8	8
8	8	8	8	8	8	8	8	7	7	7	7	7	7	7	7	7	7	7	7	7	6	6	6	6
6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

TIME= 15.50 SECONDS TO 30.00 SECONDS IN INTERVALS OF 0.50 SECONDS

1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0																				

AIR RTD INPUT CONCENTRATION CURVE NO. 13
APPLIES TO RUNS 3,4,7,8,11-15,17-19,21-28
TIME= 0.02 SECONDS TO 6.00 SECONDS IN INTERVALS OF 0.02 SECONDS

118	229	333	429	517	598	671	737	795	845	888	924	951	972	984	990	987	977	959	934	901	861	813	758	695
686	676	666	656	644	633	621	608	595	581	567	552	537	521	504	487	470	452	433	414	395	374	354	333	311
297	283	270	257	245	233	222	212	202	192	183	175	167	159	153	146	141	135	131	127	123	120	117	115	114
112	110	108	106	104	102	101	99	98	96	95	94	92	91	90	89	88	87	86	85	85	84	83	83	83
81	81	80	79	78	77	76	75	75	74	73	72	72	71	71	70	70	69	69	68	68	68	67	67	67
66	65	64	63	62	61	60	60	59	58	58	57	56	56	55	55	54	54	53	53	52	52	52	52	51
51	50	50	49	49	49	48	48	47	47	47	46	46	46	46	45	45	45	45	45	44	44	44	44	44
44	44	43	43	43	42	42	42	42	42	41	41	41	41	41	40	40	40	40	40	39	39	39	39	39
39	39	38	38	38	38	37	37	37	37	36	36	36	35	35	35	34	34	33	33	33	32	32	31	31
31	31	30	30	30	30	30	30	30	30	30	30	30	29	29	29	29	29	29	28	28	28	28	28	28
27	27	27	27	27	26	26	26	26	26	26	26	25	25	25	25	25	25	25	25	25	25	24	24	24
24	24	24	24	24	24	24	24	24	24	24	23	23	23	23	23	22	22	22	22	21	21	21	21	20

TIME= 6.20 SECONDS TO 12.00 SECONDS IN INTERVALS OF 0.20 SECONDS

20	20	20	20	20	20	20	20	20	20	19	18	16	15	14	13	12	11	11	10	9	9	8	7	7
6	6	5	5	5																				

AIR RTD INPUT CONCENTRATION CURVE NO. 14
APPLIES TO RUNS 1,2,6,10,16,20
TIME= 0.02 SECONDS TO 6.00 SECONDS IN INTERVALS OF 0.02 SECONDS

0	0	0	0	0	48	112	192	288	400	514	617	707	784	850	902	943	971	986	990	982	969	951	928	900
866	827	783	734	680	648	619	591	564	540	516	495	475	456	440	418	399	381	364	350	336	325	315	306	300
290	280	270	260	250	240	230	220	210	200	194	188	182	176	170	164	158	152	146	140	135	130	126	123	120
117	114	112	111	110	108	106	104	102	100	98	96	94	92	90	89	88	87	86	85	84	83	82	81	80
79	79	78	77	76	76	75	74	73	73	72	71	71	70	70	69	68	68	67	67	66	66	65	65	64
64	63	63	63	62	62	62	61	61	61	60	60	60	60	60	59	59	58	58	58	57	57	56	56	56
55	55	54	54	54	53	53	52	52	52	51	51	50	50	50	49	49	48	48	48	47	47	46	46	46
45	45	44	44	44	43	43	42	42	42	41	41	40	40	40	39	39	39	38	38	38	38	37	37	37
37	36	36	36	36	35	35	35	35	34	34	34	34	33	33	33	33	32	32	32	32	32	31	31	31
31	30	30	30	30	30	29	29	29	29	29	28	28	28	28	28	27	27	27	27	27	26	26	26	26
26	26	25	25	25	25	25	24	24	24	24	24	24	23	23	23	23	23	23	22	22	22	22	22	22
22	21	21	21	21	21	21	20	20	20	20	20	20	20	20	19	19	19	19	19	19	19	18	18	18

TIME= 6.20 SECONDS TO 12.00 SECONDS IN INTERVALS OF 0.20 SECONDS

17	16	15	14	13	12	11	10	10	9	8	8	7	7	6	6	5	5	5	4	4	4	3	3	3
3	2	2	2	2																				

Table A2: Output concentration curves for drying air R.T.D.

RUN 1A , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	8	21	59	215	489	882	973	990	930	796	811	807	784	742	747	731	694	634	669	699	723	742	796	828
839	828	367	893	905	903	891	893	907	936	938	936	928	914	907	903	902	903	903	903	903	903	891	882	875
871	858	839	815	785	780	774	769	764	737	710	683	656	645	624	591	548	531	516	504	494	492	484	470	451
419	258	197	151	116	88	68	52	39	30	23	17	13	10	8	6	4	3	2	2	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1A , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	94	185	274	360	402	412	391	340	358	391	440	505	519	587	710	886	928	959	979	990	983	969
947	917	921	928	937	948	942	938	937	938	938	938	938	938	935	928	915	897	903	897	877	845	853	855	853
845	858	855	837	804	808	794	761	711	689	670	653	639	622	608	596	587	587	587	587	587	583	577	568	556
391	278	213	163	125	95	73	56	43	33	25	19	14	11	8	6	5	3	2	2	1	1	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1B , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	86	99	121	151	190	246
294	333	363	359	398	480	606	649	693	736	779	816	849	877	901	931	953	966	970	981	987	990	987	990	987
981	970	964	953	938	918	920	918	912	901	907	901	881	849	838	831	829	831	823	814	805	797	766	745	732
727	697	675	662	658	649	641	632	623	615	606	597	589	580	571	563	554	545	537	528	519	511	502	493	485
242	329	274	228	190	158	132	110	91	76	63	53	44	36	30	25	21	17	14	12	10	8	7	5	4
4	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1B , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	86	99	121	151	190	246
294	333	363	359	398	480	606	649	693	736	779	816	849	877	901	931	953	966	970	981	987	990	987	990	987
981	970	964	953	938	918	920	918	912	901	907	901	881	849	838	831	829	831	823	814	805	797	766	745	732
727	697	675	662	658	649	641	632	623	615	606	597	589	580	571	563	554	545	537	528	519	511	502	493	485
242	329	274	228	190	158	132	110	91	76	63	53	44	36	30	25	21	17	14	12	10	8	7	5	4
4	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1C , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	39	63	98	142	196	227
274	335	411	426	450	485	529	588	646	705	764	789	813	838	862	883	901	917	931	948	960	967	970	985	990
985	970	966	960	952	940	940	940	940	940	918	901	889	882	874	862	845	823	812	803	797	793	773	754	738
725	710	695	681	666	656	646	637	627	623	617	608	597	589	578	564	548	546	539	526	509	497	490	487	490
401	343	288	242	204	171	144	121	102	85	72	60	51	42	36	30	25	21	18	15	12	10	9	7	6
5	4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1C , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	39	63	98	142	196	227
274	335	411	426	450	485	529	588	646	705	764	789	813	838	862	883	901	917	931	948	960	967	970	985	990
985	970	966	960	952	940	940	940	940	940	918	901	889	882	874	862	845	823	812	803	797	793	773	754	738
725	710	695	681	666	656	646	637	627	623	617	608	597	589	578	564	548	546	539	526	509	497	490	487	490
401	343	288	242	204	171	144	121	102	85	72	60	51	42	36	30	25	21	18	15	12	10	9	7	6
5	4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1D , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	10	119	210	282	336	454	557	644	715	759
788	801	799	787	788	803	830	816	809	811	820	842	862	879	894	900	915	937	967	972	978	983	988	982	978
976	978	989	988	974	946	926	915	911	915	882	862	855	862	858	851	842	830	826	820	811	799	786	767	744
715	706	694	679	662	642	631	627	631	625	620	615	610	604	599	594	589	583	578	573	567	557	546	536	525
399	347	289	241	200	167	139	116	96	80	67	56	46	38	32	27	22	18	15	13	10	9	7	6	5
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1D , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	10	119	210	282	336	454	557	644	715	759
788	801	799	787	788	803	830	816	809	811	820	842	862	879	894	900	915	937	967	972	978	983	988	982	978
976	978	989	988	974	946	926	915	911	915	882	862	855	862	858	851	842	830	826	820	811	799	786	767	744
715	706	694	679	662	642	631	627	631	625	620	615	610	604	599	594	589	583	578	573	567	557	546	536	525
399	347	289	241	200	167	139	116	96	80	67	56	46	38	32	27	22	18	15	13	10	9	7	6	5
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1E , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	22	73	149	249	344	433	516	510	528	568	631	718
791	850	895	923	941	946	941	946	952	958	964	978	987	989	987	971	964	965	975	977	975	971	964	961	952
938	918	913	906	896	883	868	849	827	803	799	791	781	769	763	757	751	746	740	734	728	723	720	711	697
677	664	654	647	642	639	631	616	596	594	585	571	550	538	528	520	516	499	482	464	447	450	447	439	424
344	275	227	187	154	127	105	86	71	59	48	40	33	27	22	18	15	12	10	8	7	5	4	3	3
2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1E , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	7	19	37	59	114	159	194	219	234	259	294	339	380
428	485	548	586	628	675	728	731	748	776	817	850	877	900	917	933	947	958	967	980	987	990	987	988	987
983	977	981	977	966	947	942	937	932	927	921	907	886	857	840	827	820	817	820	817	810	797	788	778	768
758	741	728	716	708	689	668	644	618	595	578	566	558	558	558	558	558	559	558	554	548	534	518	499	478
408	339	279	230	190	157	129	106	88	72	59	49	40	33	27	22	18	15	12	10	8	7	5	4	4
3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A2 (continued)

RUN 2A , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	8	21	59	215	489	882	973	990	930	796	811	807	784	742	747	731	694	634	669	699	723	742	796	828	
839	828	867	893	905	903	891	893	907	936	938	936	928	914	907	903	902	903	903	903	903	903	891	882	875	
871	858	839	815	785	780	774	769	764	737	710	683	656	645	624	591	548	531	516	504	494	492	484	470	451	
419	258	197	151	116	88	68	52	39	30	23	17	13	10	8	6	4	3	2	2	1	1	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2A , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	94	185	274	360	402	412	391	340	358	391	440	505	519	587	710	886	928	959	979	990	983	969	
947	917	921	928	937	948	942	938	937	938	938	938	938	938	935	928	915	897	903	897	877	845	853	855	853	
845	858	855	837	804	803	794	761	711	689	670	653	639	622	608	596	587	587	587	587	587	583	577	568	556	
391	278	213	163	125	95	73	56	43	33	25	19	14	11	8	6	5	3	2	2	1	1	1	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2B , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	28	79	155	217	268	309	339	397	
452	503	551	654	735	795	834	841	848	855	862	857	862	878	905	919	933	947	961	981	990	988	975	958	947	
944	947	959	961	952	933	915	905	901	905	891	876	862	848	855	862	869	876	869	862	855	848	850	848	843	
834	811	792	776	763	746	731	718	707	697	689	683	678	662	647	633	622	612	604	598	594	582	569	554	537	
415	381	318	265	220	184	153	127	106	88	73	61	51	42	35	29	24	20	17	14	11	9	8	6	5	
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2B , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	28	79	155	217	268	309	339	397	
452	503	551	654	735	795	834	841	848	855	862	857	862	878	905	919	933	947	961	981	990	988	975	958	947	
944	947	959	961	952	933	915	905	901	905	891	876	862	848	855	862	869	876	869	862	855	848	850	848	843	
834	811	792	776	763	746	731	718	707	697	689	683	678	662	647	633	622	612	604	598	594	582	569	554	537	
415	381	318	265	220	184	153	127	106	88	73	61	51	42	35	29	24	20	17	14	11	9	8	6	5	
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2C , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	55	104	167	242	298	335	354	417	
485	557	634	699	746	774	783	762	764	790	839	869	895	916	932	943	951	957	960	965	970	974	979	985	988	
990	988	988	988	988	988	984	979	974	970	960	951	942	932	923	914	904	895	886	876	867	858	847	839	833	
830	819	811	805	802	797	792	788	783	763	746	731	718	710	690	658	615	594	578	566	559	551	541	528	513	
419	354	317	251	202	163	131	105	85	68	55	44	35	28	23	18	15	12	9	7	6	5	4	3	2	
2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2C , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	43	53	71	96	129	120	
157	242	373	432	473	496	502	581	645	695	731	758	789	823	860	893	918	936	946	964	975	979	975	966	961	
959	961	968	975	982	990	982	975	968	961	945	932	923	918	909	903	902	903	891	875	855	832	828	817	799	
774	769	760	747	731	710	688	667	645	636	631	629	631	631	631	631	631	624	616	609	602	606	602	591	573	
487	373	315	279	225	181	146	117	94	76	61	49	39	32	25	20	16	13	10	8	7	5	4	3	2	
2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2D , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	5	13	23	36	48	65	84	108	134	164	197	234	270	
312	360	414	473	537	608	684	734	778	815	846	869	886	896	900	915	929	942	954	964	974	982	990	976	963	
949	936	922	909	895	882	879	875	870	864	856	848	838	828	826	823	817	810	799	787	772	756	739	724	712	
702	694	688	685	684	669	656	644	632	621	610	600	591	583	576	569	563	557	552	549	545	543	541	540	540	
468	396	342	270	210	164	128	100	78	61	47	37	29	22	17	13	10	8	6	5	4	3	2	1	1	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2D , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	11	25	42	62	85	111	140	172	141	131	141	172	223	296	388	501	607	
697	772	831	874	901	913	909	922	935	946	956	965	974	981	988	989	990	989	988	985	982	977	972	969	966	
962	956	950	942	934	925	918	911	903	893	883	872	860	846	832	817	801	784	766	746	726	705	688	672	657	
643	629	617	606	595	573	551	531	511	494	477	462	447	435	423	413	403	396	389	384	380	377	375	375	376	
313	219	141	109	85	66	52	40	31	24	19	15	11	9	7	5	4	3	2	2	1	1	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2E , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	52	97	156	262	347	410	451	447	
486	568	694	751	798	838	868	893	903	927	955	963	972	981	990	976	966	959	955	954	957	963	972	968	963	
959	955	950	946	942	937	940	937	931	920	905	885	861	833	823	814	806	798	792	788	784	781	776	768	758	
746	732	716	697	677	662	649	636	625	614	605	597	590	580	570	562	555	549	544	541	538	528	518	510	503	
434	364	300	248	204	168	139	114	94	78	64	53	43	36	29	24	20	16	13	11	9	7	6	5	4	
3	2	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 2E , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	14	69	117	158	191	233	294	373	471	513	
559	609	662	715	765	811	853	877	897	914	927	945	956	960	956	966	975	981	986	989	990	989	986	967	951	
938	927	919	914	912	912	904	894	882	868	852	835	816	794	771	750	734	721	712	706	704	706	699	691	684	
677	669	662	655	647	643	636	628	618	606	592	576	559	557	553	549	544	538	531	523	515	502	491	480	471	
380	323	267	220	181	149	123	102	84	69	57	47	38	32	26	21	18	14	12	10	8	6	5	4	3	
3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Table A2 (continued)

RUN 3A , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	30	416	786	986	878	786	894	863	786	832	863	878	848	832	786	771	755	678	632	585	585	524	
555	493	431	385	354	339	323	292	292	262	262	246	246	231	200	198	196	193	189	185	180	174	168	161	154	

RUN 4A , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	12	20	31	43	52	63	78	95	116	
139	165	194	226	261	266	270	273	275	276	275	273	270	266	261	277	304	341	390	450	521	603	696	800	915	
857	842	741	770	784	741	741	668	552	503	461	421	388	363	332	305	231	261	285	276	234	159	153	145	135	
123	120	116	109	101	97	93	89	85	81	78	75	71	68	65	63	60	57	55	53	50	48	46	44	42	

RUN 5A , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
17	38	64	95	130	179	226	272	317	360	403	444	484	522	559	603	643	679	711	739	763	782	798	810	817	
879	959	966	962	951	863	797	732	667	618	539	495	436	384	330	304	270	242	213	193	177	161	147	130	118	
109	101	93	87	80	76	72	68	63	60	56	52	48	46	44	42	39	37	35	33	32	30	28	27	26	

RUN 5B , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	8	25	49	79	117	161	212	270	311	350	388	425	461	495	528	560	591	620	650	678	702	724	743	
760	774	785	793	799	802	805	809	813	817	822	826	831	836	842	846	851	857	864	872	882	892	903	915	928	
983	983	977	946	915	872	811	725	670	602	532	489	434	403	362	334	307	285	264	239	215	202	190	175	163	
151	140	129	121	114	108	103	98	93	89	86	84	83	81	79	75	71	68	64	61	58	55	52	49	46	

RUN 5C , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	11	22	35	51	69	
99	126	152	176	198	217	235	251	266	278	291	304	318	332	347	363	379	396	413	431	462	492	521	550	577	
605	631	657	682	706	747	783	815	843	866	886	901	911	918	920	927	934	940	945	950	954	957	960	962	963	
968	990	963	904	845	797	781	717	663	604	545	490	468	428	404	373	345	321	288	264	250	239	223	207	192	
171	163	155	146	138	130	123	115	108	102	97	94	90	87	83	79	75	71	67	63	60	57	54	51	48	

RUN 5D , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	6	9	13	17	22	28	
32	39	47	57	69	83	99	117	137	159	177	196	215	234	253	273	293	314	334	355	374	394	416	440	466	
493	522	554	587	621	657	688	716	740	760	776	788	796	800	800	798	797	799	803	809	817	828	841	856	874	
932	984	978	972	891	829	776	732	692	652	604	560	506	474	437	398	359	331	312	290	275	261	246	229	210	
196	184	172	163	153	144	134	128	122	117	111	104	96	92	88	83	79	75	71	67	64	60	57	54	51	

RUN 5E , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	16	26	39	54	71	
87	105	125	147	170	195	223	251	282	315	350	384	416	448	477	506	533	559	583	606	636	664	689	714	736	
756	775	791	806	819	836	851	865	879	891	901	911	919	927	933	935	937	940	943	946	950	955	959	965	970	
990	984	959	946	913	853	787	743	702	645	593	557	520	481	435	413	394	372	349	327	299	277	260	236	219	
200	188	177	167	158	149	141	134	128	122	116	109	102	84	67	63	60	57	54	51	48	46	43	41	39	

RUN 6A , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	2	9	22	39	61	109	167	235	313	401	492	585	681	779	880	905	913	904	877	833	
842	855	874	897	926	948	965	978	985	988	990	989	986	980	972	954	935	917	898	880	870	865	865	870	880	
891	887	868	835	787	754	724	696	671	648	636	623	611	599	586	572	560	551	544	540	545	544	534	518	494	
339	231	185	123	99	80	65	52	42	34	27	22	18	14	11	9	7	6	5	4	3	2	2	1	1	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 6A , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	8	22	44	72	114	146	169	183	188	205	223	240	257	275	343	397	438	465	477	
563	635	693	737	767	820	864	899	925	941	963	979	988	989	984	980	974	965	954	941	922	905	890	878	868	
848	831	820	813	811	808	801	790	773	753	726	704	687	674	666	656	644	629	612	593	567	545	527	514	506	
318	246	188	130	105	85	68	55	44	36	29	23	19	15	12	10	8	6	5	4	3	2	2	1	1	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Table A2 (continued)

RUN 6B , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	17	36
51	65	80	95	109	145	172	190	200	201	207	234	282	350	439	551	640	706	749	768	749	736	728	727	731
782	823	856	880	896	920	941	960	975	987	990	989	985	979	969	950	937	930	928	932	921	915	915	921	932
932	932	932	932	932	916	902	891	883	878	863	848	834	819	804	790	775	760	746	731	698	670	648	632	621
530	439	347	274	225	184	151	124	101	83	68	56	46	37	31	25	20	17	14	11	9	7	6	5	4
3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6B , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	15	31
42	89	170	287	440	480	509	524	528	518	570	620	667	712	754	814	861	895	917	927	939	952	964	977	990
990	990	990	990	990	983	977	971	964	958	966	972	975	976	974	966	960	957	956	958	956	948	935	918	895
885	871	856	837	817	800	780	758	734	707	684	666	654	646	644	631	619	606	594	581	566	555	545	538	534
424	345	282	220	180	148	121	99	81	67	55	45	37	30	24	20	16	13	11	9	7	6	5	4	3
2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6C , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	39	52	59	61
68	74	80	86	92	90	107	144	201	278	350	417	479	536	588	623	661	701	744	789	830	866	897	923	944
960	971	977	978	975	985	990	990	985	975	960	949	939	933	928	922	916	910	903	897	869	845	827	813	804
770	740	715	695	681	666	655	645	638	634	628	622	616	609	603	591	578	566	554	541	527	515	506	499	495
356	325	263	216	182	153	128	108	91	76	64	54	45	38	32	27	22	19	16	13	11	9	8	6	5
4	4	3	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6C , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	125
167	203	235	261	282	347	409	469	526	581	653	713	760	795	817	827	841	856	874	895	908	920	933	946	958
964	971	977	983	990	983	977	971	964	958	950	944	941	940	942	926	915	908	907	911	900	887	871	853	832
812	793	778	764	754	735	716	697	678	660	635	618	609	607	612	618	616	607	590	565	553	540	528	515	502
408	330	282	220	185	155	130	110	92	77	65	55	46	38	32	27	23	19	16	13	11	9	8	6	5
4	4	3	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6D , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42	83	120	155	187	196	202	205	206	204
218	241	271	310	357	432	507	582	657	732	777	816	851	879	902	927	946	960	968	970	979	985	989	990	987
990	989	985	979	970	972	972	968	962	953	922	896	876	861	851	848	840	827	808	783	765	753	746	745	749
738	733	733	738	749	737	723	706	686	664	641	622	605	590	579	572	565	558	551	545	531	517	504	490	476
391	306	255	204	171	144	121	102	85	72	60	51	42	36	30	25	21	18	15	12	10	9	7	6	5
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6D , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	21	41	68
149	209	251	272	274	328	376	417	451	479	523	567	611	655	698	747	789	825	854	877	902	923	939	951	959
973	983	988	990	986	986	986	986	986	986	982	976	968	958	945	929	912	896	879	863	836	816	802	795	794
791	784	776	766	753	741	730	722	716	712	696	679	663	646	630	615	598	579	558	534	514	499	488	481	479
411	328	274	232	195	164	138	116	97	82	69	58	48	41	34	29	24	20	17	14	12	10	8	7	6
5	4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6E , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46	104	173	253	343
391	433	472	506	536	636	713	765	793	797	817	832	843	850	852	861	873	887	903	921	926	932	937	943	948
961	971	980	986	990	980	969	955	939	921	895	875	858	846	838	833	827	822	816	811	801	790	776	760	742
726	709	693	676	660	649	638	627	616	605	605	605	605	605	605	606	606	603	598	591	594	593	587	578	563
453	398	316	247	205	171	142	118	98	81	67	56	46	38	32	26	22	18	15	12	10	8	7	6	5
4	3	2	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6E , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	13	24	38	55
129	192	244	283	311	399	487	575	663	751	772	785	789	783	770	799	828	858	887	916	931	946	960	975	990
990	990	990	990	990	973	959	948	940	935	941	939	928	908	880	860	847	840	838	843	845	844	841	834	825
803	781	759	737	715	700	685	671	656	641	634	627	619	612	605	597	590	583	575	568	561	553	546	539	531
458	366	311	256	213	177	147	122	101	84	70	58	48	40	33	27	23	19	16	13	11	9	7	6	5
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 7A , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	19	49	88	136	193	259	297	331	360	384	402	416	425	429	428	422	452	480	507	532	556
578	599	618	636	652	701	745	785	821	853	881	904	923	938	949	961	970	978	984	988	990	989	988	984	978
863	719	623	546	489	402	297	249	230	172	145	119	97	76	73	67	58	172	188	38	35	32	29	27	24
22	20	19	17	16	14	13	12	11	10	9	8	8	7	6	6	5	5	4	4	4	3	3	3	2

RUN 8A , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	95	95	127	191	286	314	334
346	350	334	350	398	478	539	589	627	653	667	701	754	828	862	892	918	940	960	972	976	972	982	988	990
988	974	956	934	908	880	860	848	844	826	812	802	796	786	780	778	780	788	796	804	812	808	812	824	844
717	494	366	254	191	175	143	111	95	81	69	59	50	43	37	31	27	23	19	16	14	12	10	8	7
6	5	4	4	3	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A2 (continued)

RUN 9A , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	23	45	73
103	141	183	229	280	329	373	414	450	482	510	534	553	569	580	595	609	621	631	640	646	651	654	655	655
674	720	866	970	987	955	834	797	747	716	632	545	486	436	390	349	319	290	255	224	199	184	167	153	144
132	123	113	105	98	90	86	80	76	71	67	63	61	57	55	51	48	46	44	40	38	36	34	32	28

RUN 9A , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	25	54	87	148	206	258	306	350	389	424	454	479	500	521	542	564	587	610	634	658	684	710	736
706	889	990	957	909	863	865	836	776	692	648	593	535	492	465	436	372	326	285	258	235	212	191	174	157
141	128	117	109	102	94	83	76	71	64	61	56	51	47	42	41	37	35	32	30	27	25	22	22	18

RUN 9B , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	2	11	23	40	56	71	84	96	106	115	122	128	132
224	455	712	836	954	980	941	947	903	780	669	576	505	417	348	298	250	211	178	149	131	116	105	96	89
83	77	72	67	63	60	57	54	53	50	48	46	44	43	41	40	37	36	34	33	30	28	28	27	25

RUN 9B , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	2	11	21	31	51	70	89	108	127	146	165	184	203	221	227	235	243	253	264	277	290	305	321	338
556	740	854	911	958	990	967	976	937	854	757	689	604	512	424	351	296	253	214	182	155	137	120	110	101
90	84	77	71	65	61	56	52	50	46	45	43	41	39	37	33	33	31	30	26	26	26	22	22	20

RUN 9C , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
34	57	83	112	145	161	177	193	209	224	240	256	272	288	304	324	344	364	384	405	425	446	467	488	509
747	871	945	988	952	833	795	770	724	671	595	534	477	446	416	400	368	337	304	262	231	205	186	168	153
140	128	120	110	100	92	85	77	74	69	64	59	56	52	49	46	42	39	38	34	33	29	29	29	26

RUN 9C , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	3	9	17	27	39	52	68	85	104	125	140	156	173	191	211
233	255	279	304	331	346	364	386	410	437	466	499	534	573	614	640	666	690	714	736	758	778	798	816	833
918	959	983	981	990	946	916	824	780	719	672	608	538	528	490	458	413	386	361	326	299	274	250	225	202
180	162	149	138	128	118	108	101	92	86	79	72	68	61	56	53	50	45	41	40	36	34	31	28	25

RUN 9D , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16	33	52	73	96	107	122	141	165	194
226	264	305	351	401	437	470	501	530	556	580	602	621	638	653	682	709	734	756	777	794	810	823	834	843
867	941	987	984	939	863	852	836	773	701	673	643	573	538	469	434	401	375	349	305	271	253	234	220	203
188	179	166	144	135	131	122	111	99	90	85	77	68	62	59	53	49	46	42	37	33	31	27	25	24

RUN 9D , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	5	22	40	58	76	95	114	134	135	139	145	154	164	177	192	209	229	251	259	267	277	286	297
307	319	331	343	356	364	373	386	400	417	437	459	483	509	538	559	578	597	615	632	648	664	678	692	705
874	922	960	987	933	847	803	774	762	701	647	626	590	557	490	429	391	362	333	302	279	260	245	228	208
193	180	162	149	136	124	113	101	95	88	80	72	69	65	61	57	51	49	46	44	38	36	34	32	30

RUN 9E , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	8	18	29	40	60	81	103	126	150	176	202	230	259	289	322	354	387	418	450
480	511	541	571	600	643	682	715	744	767	785	799	807	811	810	810	810	810	811	811	812	812	813	814	814
862	937	967	963	924	847	767	729	711	667	559	508	494	448	410	391	379	363	338	306	281	265	252	234	217
201	183	165	150	140	132	122	114	106	98	91	85	76	72	67	63	60	55	52	47	45	42	39	36	34

RUN 9E , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	18	39	60	81	102	124	145	167	189	210	234	260	287	315	346
378	411	447	484	522	558	594	629	663	697	731	764	797	830	861	871	878	884	888	890	891	890	888	884	878
921	980	980	939	858	822	806	746	685	650	605	564	515	465	421	393	373	351	322	293	270	254	243	229	210
191	174	158	146	140	129	117	110	100	93	86	81	75	68	63	57	54	52	48	45	41	37	36	34	30

Table A2 (continued)

RUN 10A , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	14	42	79	126	183	249	325	470	595	699	784	850	895	920	926	912	878
898	915	929	940	949	954	957	957	954	949	970	984	990	987	977	959	933	899	857	807	772	740	712	687	665
647	632	621	613	609	600	592	583	575	566	558	549	541	532	524	508	494	479	466	453	440	428	417	406	396
311	240	184	141	118	99	83	70	62	54	47	41	36	32	28	24	21	19	16	14	12	11	9	8	7
6	5	5	4	3	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0

RUN 10A , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	8	32	69	118	180	255	342	442	556	666	760	838	900	946	976	990	987	969	934
934	932	927	920	910	899	884	868	849	828	813	799	785	771	757	742	728	714	700	686	681	678	676	674	674
674	676	678	681	686	678	670	660	650	638	626	613	599	583	567	563	556	546	534	520	503	485	463	440	414
359	307	258	212	167	130	102	82	72	63	55	49	43	37	33	29	25	22	19	17	15	13	11	10	8
7	6	6	5	4	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0

RUN 10B , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	14	33	56	84	118	174	229	284	339	393	446	499	552	604	655
690	723	754	784	813	839	865	888	910	931	945	958	969	977	983	987	989	990	987	983	969	955	942	930	918
906	895	885	875	865	849	834	818	802	786	771	755	739	724	708	688	667	646	625	603	580	557	534	509	485
324	209	140	118	96	78	63	52	45	39	34	30	26	22	19	17	15	13	11	9	8	7	6	5	4
4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 10B , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	3	5	7	10	62	114	168	223	280	337	396	457	518	581
599	619	641	664	689	716	744	774	806	840	875	905	931	952	969	980	987	989	987	980	967	952	934	915	893
870	844	816	786	753	754	753	748	741	732	720	705	688	668	646	621	597	573	550	527	505	483	461	440	420
242	129	80	96	79	64	52	43	37	32	28	24	21	18	16	14	12	10	9	8	7	6	5	4	4
3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 10C , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	14	33	58	89	126	168	216	269	328	392	410	433	461	495	533	576	624	677	736	799
835	867	895	919	940	956	968	977	981	982	988	990	987	979	968	951	931	905	876	841	830	819	808	796	785
774	763	752	740	729	722	713	702	689	673	655	635	612	588	561	552	542	530	518	505	490	474	457	440	420
354	294	242	196	152	119	96	84	73	63	55	48	42	36	31	27	24	21	18	15	13	12	10	9	7
6	6	5	4	3	3	3	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0

RUN 10C , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	11	29	56	92	137	190	251	322	401	455	507	557	604	648	690	729	767	801	833
861	886	907	926	941	954	963	969	972	972	977	980	983	986	988	989	990	990	989	988	973	959	943	927	910
893	875	857	838	818	804	791	779	767	756	746	736	726	718	710	699	687	675	662	648	634	619	604	587	571
418	308	241	216	172	138	114	100	87	76	66	57	50	43	38	33	28	25	21	19	16	14	12	10	9
8	7	6	5	4	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0

RUN 10D , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	110	188	282	392	492	581	660	728	785	832	869	895	911	916	940	959	974	984	989	990	985	977	963	945
918	894	874	857	843	834	827	824	825	829	822	815	810	804	800	796	792	789	787	785	783	779	773	765	756
745	732	718	701	683	664	645	627	611	596	582	569	558	547	538	528	519	510	502	494	487	481	475	470	465
385	320	269	232	192	160	134	116	101	88	76	66	58	50	44	38	33	29	25	22	19	16	14	12	11
9	8	7	6	5	4	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0

RUN 10D , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	128	191	254	316
376	436	496	554	612	672	726	773	814	849	877	899	915	925	928	916	908	904	904	908	916	928	944	963	987
989	990	990	989	987	985	982	978	973	967	959	952	944	936	928	920	912	904	896	888	884	877	869	860	849
836	822	806	789	770	752	736	720	705	691	677	665	653	642	632	621	610	598	586	572	558	543	527	511	493
420	355	297	246	202	167	143	128	111	97	84	73	64	55	48	42	36	32	27	24	21	18	16	13	12
10	9	8	6	6	5	4	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0

RUN 10E , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	7	13	22	32
44	58	75	93	113	166	221	280	340	404	470	539	610	683	760	795	828	857	883	905	925	941	954	964	970
980	986	990	990	986	980	970	957	941	922	924	923	920	914	905	894	881	865	846	825	810	797	788	781	776
774	775	778	784	792	760	733	711	693	679	670	665	665	670	679	669	657	644	630	614	597	579	560	539	517
440	372	311	258	214	177	149	129	115	102	91	81	72	64	57	51	45	40	36	32	28	25	22	20	18
16	14	12	11	10	9	8	7	6	5	5	4	4	3	3	2	2	2	2	1	1	1	1	1	1

RUN 10E , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	110	174	244	320
402	491	585	686	792	838	878	912	940	961	977	986	990	987	978	963	950	940	932	927	925	926	929	936	944
945	944	940	935	927	918	906	893	877	860	842	827	813	802	792	785	780	776	775	776	773	768	761	753	742
729	714	697	678	657	647	637	627	617	607	597	587	576	566	556	551	545	538	531	523	514	504	494	483	472
388	320	269	236	200	168	141	118	105	93	83	74	66	59	52	46	41	37	33	29	26	23	20	18	16
14	13	11	10	9	8	7	6	5	5	4	4	3	3	2	2	2	2	1	1	1	1	1	1	0

Table A2 (Continued)

RUN 11A , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	2	11	25	45	93	135	172	203	225	270	338	428	541	631	699	744	825	880	
909	913	908	913	930	958	974	981	980	970	960	958	966	981	981	981	981	981	989	981	956	913	865	823	786	
755	720	688	658	631	613	597	585	575	561	552	550	552	531	507	480	451	442	428	408	383	365	349	337	327	
248	191	135	112	90	67	60	53	47	42	37	33	30	26	23	21	19	16	15	13	11	10	9	8	7	
6	5	5	4	4	3	3	2	2	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	

RUN 12A , SUBRUN , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	
15	23	31	62	125	219	345	439	501	533	533	570	627	703	799	882	940	976	988	988	988	988	988	990	988	
982	972	962	940	907	862	837	815	797	784	770	752	731	705	693	674	646	611	599	580	552	517	482	454	435	
423	396	376	364	360	343	326	310	294	280	266	253	241	230	219	209	200	192	185	178	172	167	163	159	156	
94	62	47	39	33	28	24	21	18	15	13	11	9	8	7	6	5	4	3	3	2	2	2	1	1	
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 13A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
14	129	201	288	562	793	865	865	923	952	966	980	980	908	880	807	735	706	692	678	649	634	605	577	504	
461	432	375	331	302	271	242	216	193	173	155	141	129	121	115	109	103	97	91	86	81	77	72	68	64	

RUN 14A , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
38	217	491	674	748	831	899	966	988	935	875	795	712	659	631	575	519	458	399	350	312	283	264	243	218	
207	185	166	151	132	119	111	106	99	93	86	84	82	76	70	63	61	63	61	54	55	50	46	46	46	

RUN 14A , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	5	12	19	26	32	38	43	48	52	56	60	63	65	68	69	71	71	72	72	72	71	69	68	
69	70	71	72	73	74	74	75	76	76	77	77	78	78	78	78	79	79	79	79	78	78	78	78	77	
77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77	
77	78	78	78	79	80	80	81	82	84	85	86	88	90	91	93	95	98	100	102	105	108	110	113	116	
174	394	629	764	905	974	988	960	924	876	783	684	588	521	486	472	446	416	393	369	330	296	269	248	233	
208	196	185	172	165	149	134	122	114	107	107	102	92	86	87	88	82	79	76	68	68	63	58	58	58	

RUN 14B , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	26	96	172	301	470	660	877	969	987	957	880	732	638	561	485	407	340	292	249	213	185	162	
141	124	112	100	88	82	76	70	65	62	56	52	50	47	44	44	42	41	40	37	33	32	31	29	29	

RUN 14B , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	4	44	125	200	309	461	626	787	898	969	988	958	885	772	668	574	494	425	366	319	277	237	205	
177	156	140	125	114	104	95	90	86	79	73	69	66	63	60	57	56	55	52	53	49	48	49	48	45	

RUN 14C , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	1	1	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1	15	38	75	132	211	317	455	608	763	887	965	989	955	873	759	661	574	487	406	331	271	225	189	159	
137	120	107	96	87	81	75	68	63	60	58	52	47	45	45	42	39	36	33	34	30	29	28	26	26	

RUN 14C , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	0	6	62	172	381	548	671	785	902	963	988	957	890	816	717	609	500	411	340	273	226	192	160	135	
112	97	84	73	64	55	50	45	42	43	38	37	38	37	32	32	29	27	26	21	22	19	13	10	10	

Table A2 (continued)

RUN 14D , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	18	34	68	134	319	475	640	801	917	970	989	958	890	804	694	601	513	427	352	296	240	194	161	134	
117	102	90	80	69	66	60	54	51	47	44	40	39	38	34	34	34	32	30	30	26	23	21	21	21	

RUN 14D , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	3	48	118	221	367	514	661	793	907	981	979	888	779	689	572	468	373	299	255	206	168	139	119	106	
92	83	77	70	63	56	52	49	45	42	38	37	38	37	34	34	34	34	34	34	34	34	34	34	34	

RUN 14E , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	110	293	402	397	499	631	753	855	972	982	988	955	895	846	737	648	564	480	408	337	281	239	204	172	
144	122	107	95	86	76	70	66	62	57	58	54	52	51	46	46	43	40	40	40	35	33	34	34	34	

RUN 14E , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	2	2	3	4	4	4	5	5	5	5	5	5	5	5	4	4	4	3	2	2	1	0	0	
0	1	1	2	2	3	3	4	4	4	5	5	5	5	5	6	6	6	6	6	6	6	5	5	5	
9	52	139	231	309	322	409	532	651	790	888	950	989	946	790	736	657	582	519	442	374	320	274	234	204	
172	148	131	118	105	101	90	80	76	71	67	63	58	54	49	49	49	46	43	44	44	41	39	38	33	

RUN 15A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	346	482	705	853	928	977	977	928	891	866	829	742	680	594	544	507	470	408	346	294	252	220	198	185	
170	155	141	126	111	99	90	83	77	74	68	63	60	57	55	53	51	47	42	37	37	37	36	34	30	

RUN 16A , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	11	28	52	84	123	170	224	273	320	
365	409	451	491	530	567	603	636	669	699	728	755	781	805	851	891	924	950	970	983	990	990	984	978	971	
963	954	945	935	924	908	892	875	858	839	820	799	778	757	737	718	699	681	664	648	633	615	597	579	562	
413	304	234	190	146	112	88	74	65	56	49	43	37	32	28	24	21	18	16	14	12	10	9	8	7	
6	5	4	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	

RUN 16A , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	27	60	108	169	243	331	433	485	533	
577	617	653	685	712	736	761	786	810	833	856	878	899	920	943	962	976	985	989	989	984	974	964	954	943	
931	918	905	891	877	864	851	837	823	807	792	775	758	746	733	719	704	687	668	649	628	610	593	576	560	
416	307	233	188	149	118	93	76	66	58	50	44	38	33	29	25	22	19	16	14	12	11	9	8	7	
6	5	4	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	

RUN 16B , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	9	22	38	59	126	188	245	297	344	386	423	455	486	519	
555	594	634	678	723	772	807	839	866	891	911	928	941	950	967	980	987	990	987	980	967	950	947	942	937	
930	922	913	902	891	882	873	863	851	838	824	808	792	777	762	747	732	717	702	688	673	663	653	643	633	
534	435	336	250	194	153	127	110	93	78	65	55	46	39	32	27	23	19	16	13	11	9	8	6	5	
4	4	3	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16B , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	51	123	215	328	417	494	562	618	663	697	721	734	773	808	
840	869	894	915	932	946	959	970	979	985	988	990	988	985	983	980	974	965	954	941	926	907	875	845	817	
792	769	748	730	714	700	685	671	656	642	627	613	598	587	577	568	560	553	548	543	540	526	512	498	485	
366	276	215	178	143	114	89	72	60	50	42	36	30	25	21	18	15	12	10	9	7	6	5	4	3	
3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Table A2 (continued)

RUN 16C , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	6	14	25	38	98	154	204	250	291	327	358	385	407	433
464	501	541	587	638	693	739	780	816	847	874	896	912	924	944	961	973	982	988	990	988	982	977	973	960
963	958	953	949	944	931	917	902	886	868	850	830	809	783	758	735	712	691	672	653	635	614	594	574	554
386	265	193	158	124	94	70	53	44	36	30	24	20	16	13	11	9	7	6	5	4	3	2	2	2
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 16C , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	99
152	206	261	319	378	439	454	475	502	536	575	620	671	728	776	819	858	893	923	950	971	989	990	987	983
975	965	953	938	920	926	927	926	920	912	900	884	865	856	846	836	824	812	798	784	769	741	713	686	659
432	274	185	150	118	94	76	63	52	43	35	29	24	20	16	13	11	9	7	6	5	4	3	2	2
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 16D , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	14	26	39	62	83
102	119	135	149	162	173	238	299	358	412	464	512	557	599	643	684	723	759	793	824	853	879	910	935	956
972	983	989	990	985	971	957	944	932	921	910	901	892	868	842	815	786	755	722	688	652	625	598	572	546
332	192	125	107	79	59	45	37	31	26	22	18	15	13	11	9	7	6	5	4	3	3	2	2	1
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 16D , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	21	30	39	50	62	75	90	108
128	150	173	198	225	255	281	313	349	390	435	485	540	600	645	688	727	765	799	830	859	885	901	916	931
945	957	969	980	990	989	986	981	975	966	956	944	930	915	898	877	855	829	800	769	735	702	670	640	610
361	202	133	122	95	75	63	55	47	39	33	27	23	19	16	13	11	9	8	7	5	4	4	3	2
2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 16E , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	10	15	21	29	37	46	88	130
173	218	263	309	357	405	444	483	522	561	600	639	678	717	752	785	815	841	865	886	904	919	941	958	972
982	988	990	988	982	961	941	922	904	887	871	856	841	806	773	743	717	693	672	654	639	613	588	564	540
339	202	129	107	88	72	59	50	42	36	30	25	21	18	15	12	10	9	7	6	5	4	3	3	2
2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 16E , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	7	17	30	46	62	83	108	138	171	210	252	299	342	379
411	437	457	471	480	483	541	595	645	690	731	768	800	828	838	848	861	874	889	906	924	943	966	981	989
990	983	969	948	920	905	889	871	851	830	808	784	759	734	710	688	667	648	630	613	598	584	570	556	542
414	302	209	143	106	76	55	42	36	30	25	21	18	15	12	10	9	7	6	5	4	3	3	2	2
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 17A , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	4	6	8	8	10	13	18	25	34	44	56	70	86	104	123	140	156	172	186	200	213	225	236
404	550	701	903	980	903	843	782	666	602	530	486	430	374	318	267	224	190	164	146	131	118	105	95	86
81	75	70	64	58	55	53	50	47	43	40	37	35	33	32	31	30	29	28	27	27	26	25	24	23

RUN 17A , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	3	6	10	14	18	22	26	30	35	39	46	53	61	70	79	89	99	110	122	135
365	596	731	914	938	922	890	810	739	612	548	496	437	397	349	311	277	245	216	190	169	151	135	122	111
104	98	92	85	79	75	71	67	64	61	59	56	53	49	45	43	42	41	39	38	37	36	35	34	33

RUN 17B , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	4	6	9	13	17	20	24	26	29	31	33	34	35	39	43	46	50	54	57	61	64	68	72
256	512	711	990	891	904	859	814	749	639	589	513	472	423	378	321	273	232	200	175	158	142	127	112	99
89	80	72	65	58	54	51	47	44	40	38	36	34	32	30	29	28	27	26	26	25	24	23	23	22

RUN 17B , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	42	72	108	150	189	222	250	273	291	303	311	312	309	300	295	293	294	298	304	314	326	341	359	379
671	715	865	918	971	980	883	777	662	609	574	534	477	419	362	315	274	239	209	185	162	141	124	109	97
89	82	76	71	66	60	55	50	47	44	41	38	37	35	35	34	33	32	31	30	29	28	27	26	25

Table A2 (continued)

RUN 17C , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	4	5	6	8	9	10	12	
97	300	486	673	956	973	908	762	591	494	454	381	324	259	210	177	149	127	109	97	86	76	69	64	60	
55	50	47	44	42	41	39	37	34	32	31	30	29	26	24	23	22	22	21	20	20	19	18	18	17	

RUN 17C , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	5	7	10	14	20	29	39	52	66	83	102	122	145	170	194	219	245	270	297	323	350	378	406	
666	750	937	979	990	937	844	739	729	656	646	614	521	458	395	340	292	250	215	187	164	144	127	114	104	
95	87	79	72	65	63	60	58	55	52	50	47	45	43	41	40	39	37	36	35	34	33	32	31	30	

RUN 17D , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	3	6	8	11	15	18	22	26	31	36	42	48	55	62	71	79	89	99	110	
204	353	432	581	849	951	809	684	550	456	400	330	267	212	172	148	127	109	96	86	79	73	68	63	58	
55	51	47	44	41	40	38	36	35	33	33	32	30	29	27	26	25	25	24	23	22	22	21	20	20	

RUN 17D , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	229	391	630	919	970	987	834	689	536	451	383	306	246	204	165	132	107	88	76	64	55	47	41	38	
34	31	28	24	21	19	17	16	15	15	15	14	14	13	11	11	11	10	10	10	9	9	9	8	8	

RUN 17E , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	7	11	15	19	
24	28	33	38	44	51	59	67	74	82	89	97	104	111	118	120	127	138	155	176	201	232	267	307	352	
638	847	935	990	891	791	638	495	396	308	236	183	143	115	96	83	72	64	57	52	48	45	42	40	39	
39	38	38	37	36	30	26	24	22	22	20	19	17	15	13	12	12	12	11	11	10	10	10	9	9	

RUN 17E , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	2	4	7	10	13	16	20	25	30	37	44	52	61	70	79	88	98	109	119	
410	620	780	880	910	775	645	660	540	430	350	280	219	170	139	116	97	83	74	70	66	61	58	53	50	
45	41	38	35	33	31	30	29	28	28	24	21	20	19	20	19	18	18	17	17	16	16	15	15	14	

RUN 18A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	3	5	8	12	29	47	67	87	108	130	154	178	203	229	254	281	307	334	362	390	418	447	477	507	
748	857	941	989	977	977	977	893	796	676	585	506	438	382	338	307	279	252	227	205	178	155	135	120	108	
98	89	79	70	60	59	57	55	52	48	45	43	41	38	36	36	36	35	33	30	29	28	27	26	26	

RUN 19A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	4	6	9	11	15	21	28	36	
46	58	71	85	101	114	130	149	170	194	220	249	280	314	351	386	421	454	486	517	547	576	604	630	656	
877	988	933	914	822	674	554	443	351	277	226	184	150	126	110	98	87	78	70	64	60	57	53	49	46	
41	38	35	33	32	30	29	28	26	25	24	23	22	21	20	19	18	17	16	16	15	14	14	13	12	

Table A2 (continued)

RUN 20A , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	9	16	24	34	46	59	74	90	108	
127	148	170	194	220	247	276	306	337	371	399	426	453	479	504	529	552	575	597	618	639	658	677	696	713	
730	745	761	775	788	803	817	830	843	856	868	880	891	902	912	922	931	940	949	957	964	971	978	984	990	
943	881	804	727	634	556	479	417	371	324	288	255	226	200	177	158	142	130	121	116	106	97	90	83	77	
72	68	65	63	61	58	55	52	49	46	44	41	39	37	35	33	31	30	28	26	25	24	22	21	20	

RUN 20A , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	43	65	88	112	136	161	187	213	240	
268	296	325	354	384	415	446	478	511	544	566	587	608	628	649	669	689	708	728	747	766	784	803	821	839	
856	874	891	908	924	934	944	952	960	967	973	978	982	985	987	989	990	989	988	986	983	979	974	969	962	
899	835	772	696	607	544	481	417	354	316	282	251	223	199	177	158	142	130	120	113	108	103	98	93	88	
83	78	73	68	63	59	56	53	50	47	45	42	40	38	36	34	32	30	29	27	26	24	23	22	20	

RUN 20B , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	21	40	62	
89	118	152	189	229	274	321	373	428	487	518	549	578	607	634	660	685	709	732	754	774	794	812	830	846	
861	875	888	900	911	913	916	919	922	925	928	931	935	939	942	946	951	955	959	964	969	974	979	984	990	
958	864	770	660	565	487	408	345	298	267	236	208	183	160	141	124	110	99	91	86	78	71	65	60	55	
50	46	43	41	39	36	34	31	29	27	25	24	22	21	19	18	17	15	14	13	12	12	11	10	9	

RUN 20B , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	21	34	50	67	87	109	132	158	185	
215	247	280	316	353	393	435	478	524	572	595	617	639	660	681	700	719	737	755	772	788	803	818	832	845	
858	869	880	891	900	907	914	921	927	933	938	944	949	953	958	962	966	969	973	976	978	981	983	985	986	
972	886	800	715	614	529	457	371	328	286	250	218	189	164	143	124	109	98	90	85	76	68	61	55	50	
45	41	38	36	35	33	31	29	27	25	23	22	20	19	17	16	15	14	13	12	11	11	10	9	8	

RUN 20C , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	2	4	8	11	15	19	24	29	35	41	121	196	267	333	395	451	504	551	594	632	
665	694	718	737	752	762	767	768	764	755	771	786	801	815	829	843	856	869	881	893	904	915	926	936	946	
956	965	973	981	989	989	989	988	986	984	981	977	973	968	962	955	948	940	931	922	912	902	890	878	865	
769	701	618	522	439	371	316	274	233	206	180	157	136	118	103	89	79	70	65	61	57	52	48	44	41	
37	34	32	29	27	25	23	21	20	18	17	16	14	13	12	11	10	10	9	8	8	7	6	6	5	

RUN 20C , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58	114	169	221	272	320	367	411	454	495	
533	570	604	637	668	696	723	748	771	792	811	829	846	863	878	892	906	918	930	940	949	958	965	972	977	
982	985	988	989	990	988	986	983	980	977	974	970	966	961	957	951	946	940	934	928	921	914	906	899	891	
792	709	610	511	429	379	330	280	231	214	190	167	148	130	115	102	92	83	77	74	67	62	57	53	49	
46	44	42	41	41	38	35	32	30	28	25	24	22	20	19	17	16	15	14	12	12	11	10	9	8	

RUN 20D , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	28	43	58	75	92	109	128	147	167	
187	208	230	252	275	299	323	348	374	401	425	450	474	498	522	545	568	590	613	634	656	677	698	719	739	
759	778	798	816	835	835	835	836	838	841	845	850	855	861	868	876	885	895	905	916	929	941	955	970	985	
985	952	918	802	718	618	551	467	401	284	245	211	181	155	133	115	101	91	85	83	75	68	61	55	50	
45	41	38	35	33	31	29	27	26	24	23	21	20	19	18	17	16	15	14	13	12	11	11	10	10	

RUN 20D , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	67	100	133	166	199	231	264	296	328	
360	391	423	454	485	516	547	578	608	638	655	673	689	706	723	739	755	771	787	802	818	833	848	863	878	
892	907	921	935	948	954	959	963	967	971	975	978	981	983	985	987	988	989	989	990	989	989	988	987	985	
930	857	784	675	583	510	437	383	328	273	242	213	188	165	145	129	115	104	96	91	86	82	79	75	72	
70	68	66	64	63	60	56	53	50	47	44	41	39	37	34	32	30	29	27	25	24	22	21	20	19	

RUN 20E , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	104	152	197	240	280	317	351	382	411	
436	459	479	497	511	523	532	539	542	543	560	578	595	613	631	648	666	684	701	719	736	754	772	789	807	
825	842	860	877	895	908	921	932	943	952	960	967	974	979	983	986	988	989	990	989	987	984	980	974	968	
910	822	719	616	513	440	381	337	293	249	221	195	172	150	132	115	101	89	80	73	68	63	59	55	51	
47	44	41	39	36	34	31	29	27	25	23	22	20	19	17	16	15	14	13	12	11	10	9	9	8	

RUN 20E , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	25	53	
86	124	167	215	268	326	389	458	531	609	650	688	725	759	790	820	847	871	894	914	931	946	959	970	978	
984	988	990	989	985	983	980	978	976	974	972	971	969	968	967	966	966	965	965	965	965	965	966	966	967	
949	842	770	663	573	483	394	340	286	250	220	192	167	144	125	108	95	84	76	71	67	63	59	56	53	
51	49	47	45	44	41	38	35	33	31	28	26	24	23	21	20	18	17	16	15	13	12	12	11	10	

Table A2 (continued)

RUN 21A , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	9	21	36	54	75	137	196	251	303	351	395	436	473	506	536	561	584	605	625	642
657	670	682	691	699	688	685	692	708	733	766	809	860	920	990	959	929	901	873	846	820	795	771	747	725
593	540	479	426	347	285	233	192	160	139	117	98	83	72	64	57	51	46	41	37	35	32	30	29	27
26	24	23	22	21	20	19	18	17	15	15	14	14	13	13	12	12	12	11	11	10	10	10	9	9

RUN 21A , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	13	29	51	78	111	149	192	238	283	326	367	407	446	483	518	552	585	607	627	645	660	674
686	695	702	708	711	800	871	926	964	985	990	977	947	901	837	833	828	820	811	800	787	773	756	738	719
622	496	437	378	322	275	233	197	167	143	122	105	92	81	74	67	61	56	52	49	45	42	40	38	37
34	31	30	29	29	28	27	26	24	23	22	22	21	20	19	19	18	17	17	16	16	15	15	14	14

RUN 21B , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	14	24	36	50
70	93	119	147	179	213	251	291	334	380	436	487	533	574	609	640	665	685	700	710	690	681	682	694	717
750	794	849	914	990	947	911	881	857	839	827	821	821	827	839	826	814	803	792	781	772	763	754	746	738
602	530	441	401	329	277	231	193	161	136	119	104	92	82	75	69	63	58	54	50	46	44	42	40	39
37	34	32	30	28	29	28	28	27	25	24	24	23	22	21	20	20	19	18	18	17	17	16	15	15

RUN 21B , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	17	29	44	61
91	120	149	178	206	233	261	287	314	340	361	382	403	423	443	462	481	500	518	536	556	575	594	611	628
644	660	674	688	700	717	733	750	766	783	799	816	832	849	865	898	926	948	966	979	987	990	987	980	968
953	834	711	618	546	467	394	328	269	216	178	147	122	104	92	82	73	65	57	51	46	43	41	40	40
36	33	31	30	30	29	28	27	25	23	22	22	21	20	19	19	18	17	17	16	16	15	15	14	14

RUN 21C , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	7	12	18	25
32	42	57	75	97	122	151	184	221	261	293	325	355	385	413	440	467	492	516	540	559	577	595	612	628
644	659	673	687	700	706	717	732	752	776	804	837	874	916	961	974	983	988	990	987	980	970	955	937	915
852	725	607	544	455	374	307	253	212	185	161	140	121	105	92	82	73	66	62	59	54	50	46	43	40
38	36	34	33	32	32	31	29	28	26	25	24	23	22	21	20	19	18	18	17	16	16	15	14	14

RUN 21C , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	6	15	26	39	55	90	125	162	199	237	277	317	358	400	443	476	506	533	557	577
595	609	621	629	634	649	664	678	691	704	716	727	738	748	757	831	891	937	968	986	990	979	954	916	863
810	704	616	528	459	405	353	302	253	206	173	145	123	105	92	82	74	66	60	54	49	45	42	41	42
38	36	34	33	32	29	27	25	25	25	24	23	22	21	20	20	19	18	17	16	16	15	15	14	13

RUN 21D , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	3	9	15	23	33	64	96	129	164	198	234	271	309	347	386	430	469	504	536	563
587	606	622	633	641	665	688	710	731	751	771	789	807	824	840	835	834	838	845	856	871	891	914	941	972
906	862	729	652	571	472	389	321	269	232	194	163	136	115	99	85	74	65	58	53	48	44	41	38	35
32	30	29	28	27	25	23	21	19	18	17	17	16	15	14	14	13	12	12	11	11	10	10	9	9

RUN 21D , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	8	20	34	52	72	114	155	194	232	269	305	339	372	404	435	450	468	489	512	539
568	601	636	674	715	732	747	762	775	788	799	809	819	827	834	869	899	925	947	964	977	985	990	989	985
865	746	653	601	508	423	352	294	249	217	185	157	134	116	103	95	87	78	70	62	57	53	50	47	44
43	41	39	36	33	32	31	30	29	29	27	26	25	24	23	22	21	20	19	18	17	16	15	15	14

RUN 21E , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	4	13	25	40	58	79	103	128	154	182	210	240
271	303	336	370	405	442	477	508	537	563	587	607	625	640	653	636	630	635	652	680	719	770	832	905	990
880	673	474	398	354	280	219	168	130	103	86	72	61	52	46	40	35	30	27	24	22	20	18	16	15
14	13	12	11	9	8	7	7	6	6	6	6	5	5	5	5	4	4	4	4	4	3	3	3	3

RUN 21E , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	2	6	11	17	24	16	16	23	36	56	82	115	156	202	256	295	332	367	401	432
462	489	515	538	560	582	603	624	644	664	684	704	723	742	760	803	841	875	904	929	949	965	976	982	985
816	688	592	480	384	303	236	183	144	120	101	86	74	67	64	56	50	46	44	44	40	38	35	34	32
30	28	27	25	24	23	22	22	21	20	19	18	17	16	15	15	14	13	13	12	12	11	10	10	10

Table A2 (continued)

RUN 22A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	6	17	34	57	85	119	158	202	253	278	305	333	361	391	421	452	485	518	552	588	624	658	692	724
756	787	817	846	874	891	907	921	933	943	951	958	962	965	966	973	979	984	987	989	990	989	986	983	978
920	793	667	540	437	346	272	214	173	149	129	111	95	81	69	62	57	52	47	43	39	36	32	30	27
24	22	20	18	17	15	14	13	11	10	9	9	8	7	6	6	5	5	4	4	3	3	3	2	2

RUN 23A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	48	94	152	220	300
395	482	559	628	687	738	779	812	835	850	846	843	844	846	850	856	864	874	886	900	920	937	952	965	975
982	987	989	990	987	977	969	962	955	950	945	942	939	938	937	935	931	927	920	912	903	891	879	865	850
712	575	462	350	287	230	182	145	117	100	97	94	92	89	87	84	82	80	77	75	73	71	69	67	65
64	62	60	59	57	55	54	52	51	50	48	47	46	44	43	42	41	40	38	37	36	35	34	33	32

RUN 24A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	3	3	11	22	45	83	121	175	220	255	293	335	373	411	445
479	502	527	548	567	586	609	632	651	673	693	712	990	982	970	944	936	921	974	951	921	967	929	929	913
906	898	891	875	868	845	822	814	792	780	761	734	715	700	693	685	677	662	654	647	643	647	639	632	624
487	396	338	281	236	194	159	137	118	106	93	82	73	64	56	50	44	38	34	30	26	23	20	18	16
14	12	11	9	8	7	6	5	5	4	4	3	3	2	2	2	1	1	1	1	1	1	0	0	0

RUN 25A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	3	6	9	12	28	49	74	103	137	176	219	267	319	375
433	483	526	561	588	609	621	626	624	614	635	657	680	703	726	750	775	800	826	852	872	891	909	925	939
952	964	974	982	990	989	987	985	981	977	971	965	957	949	939	931	922	912	901	889	876	862	847	831	814
701	551	413	288	213	158	116	86	68	62	51	41	34	28	25	21	18	15	13	11	9	8	7	6	5
4	3	3	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 26A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	13	31	54	81	113	178	242	304	365	423	480	536	589	641	692
729	762	790	814	833	848	858	863	865	861	863	867	873	880	889	900	913	927	943	960	973	982	987	990	988
984	976	965	950	932	925	917	908	899	889	879	869	857	845	833	820	806	792	778	762	747	730	713	696	678
509	369	259	178	127	101	79	62	50	42	38	34	30	27	24	22	20	18	16	14	13	11	10	9	8
7	6	6	5	5	4	4	3	3	2	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0

RUN 27A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	16	38	65	97	135	204	270	332	392	448	500	550	596	639	678
704	728	750	770	787	802	815	826	835	841	880	913	941	962	977	986	989	987	978	963	967	968	968	967	963
959	952	944	934	923	906	890	874	858	841	825	809	792	776	760	746	733	719	705	692	678	665	651	638	624
460	326	223	150	108	89	74	62	54	50	46	43	39	36	34	31	29	27	25	23	21	19	18	17	15
14	13	12	11	10	9	9	8	7	7	6	6	5	5	4	4	4	3	3	3	3	2	2	2	2

RUN 28A , SUBRUN , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	9	31	61	98	141	192	243	293	340	386	430	472	513	551	588	623
647	673	701	730	760	792	826	860	897	934	953	968	978	986	989	989	986	978	967	953	934	917	900	885	870
857	845	834	824	815	808	799	790	780	770	758	746	733	720	705	691	676	661	647	632	617	603	588	573	559
412	302	210	155	119	97	80	67	59	54	51	48	43	38	32	29	26	23	21	19	17	16	14	13	11
10	9	8	8	7	6	5	5	4	4	4	3	3	2	2	2	2	2	1	1	1	1	1	1	1

Table A3: Output concentration curves for atomising air R.T.D.

RUN 1B , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	25	68	117	229	404	642	608	619	677	780	858	918	961	987	990
987	978	964	949	941	938	941	944	941	932	918	863	826	806	803	792	780	769	757	734	711	688	665	654	642
631	619	605	596	594	596	588	573	553	528	519	505	484	459	447	436	424	413	416	413	404	390	364	344	330
321	324	321	312	298	290	282	275	268	261	254	247	241	235	229	223	218	213	208	203	199	195	190	187	183
146	114	91	72	57	45	36	28	22	18	14	11	9	7	5	4	3	2	2	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1B , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	15	41	76	123	189	287	415	574	646	697	728	738	787
820	838	841	833	841	864	902	925	943	956	964	977	984	987	984	990	984	969	943	933	923	913	902	854	820
802	800	754	718	692	677	656	636	615	595	597	595	587	574	561	553	551	553	574	574	553	512	482	451	420
389	392	389	382	369	359	348	338	328	318	307	297	287	276	266	256	246	235	225	215	205	194	184	174	164
131	102	81	64	51	40	32	25	20	16	12	10	8	6	5	4	3	2	2	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1C , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	61	140	214	283	347	367
408	469	551	605	663	723	785	830	867	896	918	927	938	953	969	983	989	988	979	967	959	956	959	960	959
955	949	955	949	930	898	871	857	856	867	864	847	813	765	757	745	727	704	687	673	662	653	648	642	637
632	630	622	609	591	573	556	540	525	510	496	483	471	459	449	439	430	422	414	408	402	397	393	390	387
347	275	242	213	187	164	145	127	112	98	86	76	67	59	51	45	40	35	31	27	24	21	18	16	14
12	11	9	8	7	6	5	5	4	3	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0

RUN 1C , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	200	533	200	0	0	0	0	0	0	0	36	80	130	186	253	320	386	453	506
560	613	666	690	720	756	800	823	853	890	933	946	960	973	986	986	986	986	986	986	986	986	986	990	986
976	960	950	933	910	880	866	853	840	826	813	800	786	773	776	773	763	746	733	720	706	693	683	666	643
613	616	613	603	586	576	566	557	548	540	532	525	518	512	506	501	497	493	489	486	484	482	481	480	479
426	346	304	268	235	207	182	160	141	124	109	96	84	74	65	57	50	44	39	34	30	26	23	20	18
15	14	12	10	9	8	7	6	5	5	4	3	3	3	2	2	2	1	1	1	1	1	0	0	0

RUN 1D , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87	154	203	232	295	355	411	464	506
556	614	680	719	757	796	835	858	881	904	928	955	974	986	990	982	974	966	959	949	943	941	943	937	928
914	897	870	850	839	835	827	819	812	804	806	804	798	788	783	773	759	742	730	711	684	649	634	618	603
587	580	572	564	556	547	538	529	519	510	501	491	482	473	464	454	445	436	426	417	408	399	389	380	371
324	278	234	196	165	139	117	98	82	69	58	49	41	34	29	24	20	17	14	12	10	8	7	6	5
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1D , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	40	75	121	184	242	295	343	447
525	578	606	631	666	712	767	795	828	866	909	944	969	984	990	977	969	967	969	969	969	969	969	974	969
954	929	919	909	899	888	868	848	828	808	790	767	739	707	681	666	661	666	664	666	674	686	691	686	671
646	636	626	616	606	595	584	573	563	553	543	533	523	514	505	496	487	478	470	462	454	446	438	431	424
363	282	237	200	168	141	118	100	84	70	59	50	42	35	29	25	21	17	14	12	10	8	7	6	5
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 1E , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	15	41	92	125	140	139	135	153	191	250	304	347	381	403	428
459	497	542	598	654	709	765	821	862	890	904	927	946	962	974	983	988	990	988	983	974	962	946	943	932
915	890	869	849	828	807	798	793	791	793	793	793	793	793	784	779	777	779	767	751	732	709	676	654	642
640	631	626	624	626	619	612	605	597	589	581	572	562	553	542	532	521	509	497	485	472	459	445	431	417
347	292	257	226	198	174	153	135	119	104	92	81	71	62	55	48	42	37	32	29	25	22	19	17	15
13	11	10	9	8	7	6	5	4	4	3	3	2	2	2	1	1	1	1	1	1	0	0	0	0

RUN 1E , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	46	104	148	208	283	374	476
572	663	749	794	832	862	884	902	915	923	926	931	936	941	947	958	967	974	978	984	988	990	988	979	967
953	936	918	905	897	895	885	874	859	842	840	832	819	801	777	759	746	738	735	728	719	707	695	686	680
676	671	666	660	655	649	642	635	629	621	614	606	599	591	582	574	565	556	547	538	529	519	509	499	489
447	395	347	305	269	236	208	183	161	141	124	109	96	84	74	65	57	50	44	39	34	30	26	23	20
18	15	14	12	10	9	8	7	6	5	5	4	3	3	3	2	2	2	1	1	1	1	1	0	0

Table A3 (continued)

RUN 2B , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	73	138	221	231	268	332	425	594
702	747	730	749	767	782	794	758	748	763	804	832	850	855	850	862	877	895	914	934	951	966	979	985	988
989	988	978	970	964	961	957	951	943	933	924	914	905	896	874	859	851	850	842	831	819	804	788	776	765
757	740	730	726	730	745	755	759	757	750	737	717	693	673	656	641	628	618	609	604	600	587	574	559	545
428	369	304	255	208	169	138	113	92	75	61	50	40	33	27	22	18	14	12	9	7	6	5	4	3
2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 2B , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	56	134	197	246	282	324
395	493	620	669	696	701	686	666	677	718	790	823	846	860	865	888	912	935	959	958	959	962	968	980	987
990	987	984	978	970	959	954	950	945	940	937	931	922	912	891	874	863	855	833	818	810	808	799	790	780
771	754	743	736	733	724	714	705	696	686	677	667	658	647	636	624	611	598	584	569	554	532	512	494	479
427	366	276	225	183	149	122	99	81	66	54	44	36	29	23	19	15	12	10	8	7	5	4	3	3
2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 2C , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	18	40	65	93	181	293	429	587	667	734	787	828	856
881	903	921	914	908	901	894	908	921	934	948	963	974	983	988	990	988	983	974	963	948	929	908	909	908
903	894	896	894	889	881	874	868	861	854	849	841	829	814	808	801	794	787	764	747	737	734	722	707	689
667	644	627	617	614	612	609	605	601	595	589	582	574	567	560	554	547	540	534	527	520	512	505	499	494
405	333	310	264	229	198	171	148	128	111	96	83	72	62	54	46	40	35	30	26	22	19	17	14	12
11	9	8	7	6	5	4	4	3	3	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0

RUN 2C , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	38	91	128	149	154	275	359	404	410	421
449	492	551	665	744	787	795	826	847	858	860	861	872	893	924	945	962	977	988	990	988	983	975	977	975
970	962	964	962	957	949	911	885	872	872	874	872	868	860	861	860	855	847	839	834	832	834	829	821	810
795	776	757	738	718	697	680	665	654	646	641	640	641	617	596	579	564	553	545	540	539	541	542	541	539
446	410	364	302	262	226	196	170	147	127	110	95	82	71	61	53	46	40	34	30	26	22	19	16	14
12	10	9	8	7	6	5	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0

RUN 2D , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	37	119	186	240	280	338	392	441	485	574
653	723	784	831	859	868	859	880	896	908	915	922	933	950	971	968	971	978	990	959	933	912	896	896	896
896	896	896	896	896	896	898	896	889	877	882	877	863	840	845	840	826	803	805	803	796	784	786	784	777
765	744	728	716	709	698	688	677	667	658	649	640	632	624	616	609	602	595	589	583	578	573	568	564	560
466	392	315	254	204	164	132	106	86	69	55	44	36	29	23	18	15	12	9	7	6	5	4	3	2
2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 2D , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	76	153	230	307	425	526	611	680	743
789	819	833	872	899	915	921	932	943	954	965	981	987	981	965	979	987	990	987	987	987	987	987	976	965
954	943	918	899	885	877	861	855	861	877	877	877	877	877	866	855	844	833	822	811	800	789	781	767	748
723	702	680	658	636	628	620	612	603	595	586	577	567	558	548	538	528	517	507	496	485	473	462	450	438
329	285	229	184	148	119	96	77	62	50	40	32	26	21	17	13	11	8	7	5	4	3	3	2	1
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 2E , SUBRUN 1 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	75	202	334	426	480	494	533	584	645	718	755	786	811	831	829
831	835	842	848	853	859	865	877	887	894	898	909	921	932	943	956	966	973	977	984	988	990	988	982	977
971	966	959	954	953	954	947	943	942	943	921	898	876	853	848	842	836	831	820	808	797	786	780	775	769
763	752	741	730	718	715	710	704	696	687	676	664	651	648	643	636	629	619	609	597	584	575	567	559	551
477	413	357	309	267	231	200	173	150	130	112	97	84	73	63	54	47	41	35	30	26	23	19	17	14
12	11	9	8	7	6	5	4	4	3	3	2	2	1	1	1	1	1	0	0	0	0	0	0	0

RUN 2E , SUBRUN 2 , DT= 0.50SECS(1ST 4 LINES) THEN 5.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	24	26	33	43	57	89	132	184	247	406
519	587	610	612	635	678	742	792	833	866	891	924	948	965	973	977	981	985	990	985	981	977	973	964	957
951	948	944	940	936	932	920	915	916	924	925	924	920	915	903	891	878	866	858	841	816	783	770	759	749
742	730	717	705	693	679	666	654	643	633	624	617	610	606	602	598	594	589	585	581	577	569	561	553	545
471	408	353	305	264	229	198	171	148	128	111	96	83	72	62	54	46	40	35	30	26	22	19	17	14
12	11	9	8	7	6	5	4	4	3	3	2	2	1	1	1	1	1	0	0	0	0	0	0	0

Table A3 (continued)

RUN 6B , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	36	45	46	41
36	38	46	62	83	164	238	305	365	419	453	497	552	616	691	749	797	834	862	880	899	915	927	237	943
964	979	988	990	984	976	968	959	951	943	901	870	850	839	838	832	823	810	794	775	758	741	725	708	691
663	639	618	601	586	580	571	559	543	523	504	488	476	466	461	452	444	435	427	419	399	383	371	362	356
335	293	272	209	176	148	124	104	88	74	62	52	44	37	31	26	22	18	15	13	11	9	7	6	5
4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6B , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	53	75	95	113	208	306	406	509	615	698	765	817	853	874	904	929	948	962	971	963	957	954	953	955
964	969	973	973	971	980	986	989	990	988	964	946	933	925	923	836	855	829	809	793	765	740	717	697	680
680	680	680	680	680	692	697	693	682	664	657	651	644	638	631	620	607	590	572	550	525	507	498	496	502
323	437	356	291	245	206	173	145	122	103	86	72	61	51	43	36	30	25	21	18	15	12	10	9	7
6	5	4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6C , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	9	19	14	37	88	168	277
324	372	419	467	514	552	592	635	682	732	764	795	827	859	891	919	941	957	967	970	959	952	948	948	950
958	966	974	982	990	989	978	959	929	891	864	841	822	805	792	765	742	723	706	693	685	677	669	661	653
637	621	605	590	574	566	558	550	542	534	529	520	508	493	475	477	476	472	465	455	447	439	431	423	415
336	277	217	168	141	119	100	84	70	59	50	42	35	29	25	21	17	14	12	10	8	7	6	5	4
3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6C , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	23	48	170	286	396	500	598
672	726	760	774	770	800	829	856	881	904	881	876	888	918	965	971	976	978	979	977	977	977	977	977	977
976	976	979	983	990	986	981	973	964	953	943	933	924	914	904	889	875	860	845	831	824	813	798	780	757
738	718	699	679	660	651	641	629	615	598	587	578	571	565	562	555	551	549	543	550	548	542	532	518	501
415	330	293	238	200	168	141	119	100	84	70	59	50	42	35	29	25	21	17	14	12	10	8	7	6
5	4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6D , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49	92	129	159	183	234	288	343	399	458
533	594	643	679	702	763	814	852	880	895	930	957	975	985	987	990	989	985	977	967	953	941	931	923	916
906	893	877	857	834	806	783	765	751	743	741	736	728	717	702	700	695	687	676	661	637	618	604	594	590
583	580	580	583	590	588	583	575	564	549	531	515	503	494	488	487	482	474	462	447	441	432	422	410	397
335	305	234	203	172	146	124	106	90	76	65	55	46	39	33	28	24	20	17	14	12	10	9	7	6
5	4	4	3	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6D , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	92	183	272	360	446	518	575	617	642	652
652	664	687	724	772	819	862	899	930	957	967	975	982	986	990	982	973	962	949	935	914	898	887	881	881
878	873	866	858	848	831	813	796	778	761	751	743	736	731	728	718	710	704	699	696	688	679	668	656	641
640	634	626	614	598	579	562	547	533	522	514	505	494	482	467	449	432	416	403	391	380	372	368	367	369
337	261	239	195	166	141	120	102	86	73	62	53	45	38	32	27	23	19	16	14	12	10	8	7	6
5	4	3	3	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RUN 6E , SUBRUN 1 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	20	37	59	86	130	184	248	320	401
506	601	687	764	832	875	907	927	936	933	946	957	965	972	976	985	990	990	985	976	970	964	958	953	947
945	938	926	910	890	871	854	840	828	818	806	795	783	772	760	756	750	741	731	717	713	707	698	687	674
670	664	655	644	631	620	608	597	585	574	561	550	541	535	531	534	533	527	517	502	489	478	469	463	459
358	287	258	222	190	163	140	120	103	88	75	64	55	47	40	35	30	25	22	18	16	13	11	10	8
7	6	5	4	4	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0

RUN 6E , SUBRUN 2 , DT= 0.20SECS(1ST 4 LINES) THEN 2.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	103	149	191	230	263	307	363	429	506
576	632	676	707	725	730	741	757	779	806	825	843	860	874	886	906	924	940	954	967	973	977	979	980	978
986	990	990	986	978	981	980	976	967	955	958	957	953	944	932	908	885	865	846	829	825	820	814	805	794
785	776	767	757	748	739	730	720	711	702	690	675	659	641	621	608	594	580	566	552	550	545	536	523	506
414	333	264	230	197	169	145	124	106	91	78	67	57	49	42	36	31	26	22	19	16	14	12	10	9
7	6	5	4	4	3	3	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Table A3 (continued)

RUN 10B , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	10	29	54	84	121	163	219	275	330	384	438	490	542	593	643	692
753	807	854	894	927	953	972	984	989	988	983	976	968	959	947	934	919	903	885	866	825	786	749	715	682
652	623	597	572	550	526	504	481	459	438	416	396	375	355	336	321	306	292	278	264	251	239	227	215	203
145	101	73	61	52	45	40	35	32	28	25	23	20	18	16	15	13	12	11	9	8	8	7	6	5
5	4	4	3	3	3	2	2	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0

RUN 10B , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	33	78	134	201	280	340	398	454	508	560	609	657	703	746	788
832	870	904	931	954	971	982	989	989	985	962	937	910	881	850	817	782	744	705	663	639	615	590	565	539
513	486	459	432	404	387	370	353	337	321	306	291	276	262	248	202	173	163	170	197	241	304	385	484	601
280	82	10	62	53	46	42	41	37	33	30	27	24	21	19	17	15	14	12	11	10	9	8	7	6
6	5	4	4	3	3	3	2	2	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0

RUN 10C , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	20	35	53	74	107	145	188	236	289	348	412	481	555	635	720	793	855	905	944	970	986	990	982	962
951	940	931	923	915	909	905	901	898	897	895	893	889	884	878	871	863	853	843	831	810	789	771	754	738
724	711	700	690	682	682	680	674	665	654	639	622	601	577	551	529	509	490	473	457	443	431	419	410	401
294	214	163	140	114	93	77	65	59	53	48	44	39	36	32	29	26	24	22	19	18	16	14	13	12
11	9	9	8	7	6	6	5	4	4	4	3	3	3	2	2	2	2	1	1	1	1	1	1	1

RUN 10C , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41	83	126	171	216
263	311	360	410	461	505	550	595	641	687	733	780	827	875	922	938	952	963	972	979	983	986	986	983	979
982	984	986	987	988	989	990	990	989	988	990	987	982	973	960	944	925	902	876	847	830	813	796	779	762
745	728	711	695	678	660	643	626	609	593	577	562	546	532	517	511	504	496	488	480	471	462	453	443	433
322	235	171	131	111	94	80	70	63	57	52	47	43	38	35	31	28	26	23	21	19	17	15	14	13
11	10	9	8	8	7	6	5	5	4	4	4	3	3	2	2	2	2	2	1	1	1	1	1	1

RUN 10D , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	50	83	122	167
217	273	334	401	474	574	663	741	808	864	909	942	964	976	976	981	984	987	989	990	989	987	984	981	976
959	944	930	918	906	895	886	877	870	864	858	851	842	833	822	810	798	784	769	752	730	708	689	671	655
640	628	616	607	599	591	582	574	566	557	549	541	532	524	515	505	495	487	480	474	469	465	462	460	460
359	278	216	174	148	125	106	90	81	73	65	59	53	47	42	38	34	31	28	25	22	20	18	16	14
13	11	10	9	8	7	7	6	5	5	4	4	3	3	2	2	2	2	1	1	1	1	1	1	1

RUN 10D , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26	54	84	116	150
186	224	263	304	348	388	430	474	520	568	618	669	723	778	835	869	899	924	945	963	976	984	989	990	986
969	952	936	920	905	890	875	861	848	835	836	836	834	829	823	815	806	794	781	765	748	731	715	699	684
669	655	641	627	614	609	603	596	588	580	570	559	548	535	522	503	485	469	454	440	428	418	408	401	394
333	278	229	185	153	127	107	92	83	75	67	60	54	48	44	39	35	31	28	25	23	20	18	16	15
13	12	11	9	8	7	7	6	5	5	4	4	3	3	3	2	2	2	1	1	1	1	1	1	1

RUN 10E , SUBRUN 1 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	92	144	200	260
325	393	466	542	623	632	644	660	679	702	729	760	794	831	872	908	937	960	976	986	989	987	978	962	941
922	905	889	874	861	849	839	830	822	816	792	770	749	731	714	699	686	674	665	657	648	639	630	621	612
603	594	585	575	566	562	557	550	542	532	521	509	496	481	464	458	451	444	437	430	424	417	410	403	396
323	260	209	170	145	124	106	90	81	73	65	59	53	47	43	38	34	31	28	25	22	20	18	16	14
13	11	10	9	8	7	7	6	5	5	4	4	3	3	2	2	2	2	1	1	1	1	1	1	1

RUN 10E , SUBRUN 2 , DT= 0.10SECS(1ST 4 LINES) THEN 1.00SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	98	190	274	351	420
482	537	585	626	659	698	734	768	800	829	857	882	904	925	943	958	969	979	985	989	990	988	983	976	966
952	939	925	911	898	884	870	857	843	829	823	815	806	796	784	771	756	740	723	704	695	684	673	661	648
633	618	603	586	568	551	535	519	503	488	474	460	446	433	420	408	398	389	381	375	370	366	364	363	363
301	250	210	181	150	125	105	90	81	73	66	59	53	47	43	38	34	31	28	25	22	20	18	16	14
13	11	10	9	8	7	7	6	5	5	4	4	3	3	3	2	2	2	1	1	1	1	1	1	1

Table A3 (continued)

RUN 16B , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	4	10	17	26	38	58	85	120	162	212	269	334	386	434	
479	521	560	595	627	655	686	717	747	775	803	831	857	882	908	929	948	963	974	983	988	990	989	986	982	
976	969	959	949	936	936	936	936	936	936	936	936	936	926	914	900	882	863	841	816	789	771	754	737	722	
593	481	396	321	255	200	154	120	97	86	73	61	51	43	36	30	25	21	18	15	12	10	9	7	6	
5	4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16B , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	15	38	66	101	123	144	166	188	209	231	253	275	302	331	
360	390	422	454	487	521	571	617	658	694	727	754	777	796	820	843	864	883	900	915	929	941	956	968	977	
984	988	990	988	984	972	961	950	941	932	924	918	912	911	908	904	897	889	879	867	854	838	823	809	796	
704	593	454	347	273	231	193	159	128	101	85	71	60	50	42	35	30	25	21	17	15	12	10	8	7	
6	5	4	3	3	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16C , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	55	97	147	227	301	
369	432	489	540	585	625	648	672	699	728	758	792	827	864	888	910	928	944	956	966	974	978	984	988	990	
989	987	982	975	966	948	928	908	887	865	843	820	796	777	759	742	728	714	702	691	682	655	631	609	591	
443	295	217	159	120	102	83	68	55	45	39	34	29	25	22	19	16	14	12	10	9	8	6	6	5	
4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16C , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	4	11	19	29	32	38	47	59	74	92	114	138	164	198	
238	287	342	405	476	554	606	655	701	742	780	814	844	871	891	909	925	940	953	964	972	980	984	987	989	
990	989	987	984	980	976	973	971	970	969	968	969	970	942	916	893	871	851	832	816	801	783	763	743	722	
514	376	275	198	142	108	92	79	68	59	51	44	38	33	28	24	21	18	16	14	12	10	9	7	6	
5	5	4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16D , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	7	16	28	44	64	87	114	155	197	
241	286	334	383	434	487	499	520	549	588	635	692	757	832	861	887	911	932	950	966	979	990	981	972	960	
946	931	914	895	875	845	816	787	760	733	708	683	660	644	627	608	588	565	541	515	487	467	448	429	410	
255	151	99	85	69	57	48	43	37	32	28	24	21	18	16	14	12	10	9	8	7	6	5	4	4	
3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16D , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	5	13	22	34	45	65	93	130	175	230	293	364	414	463	
510	555	599	641	681	720	751	782	812	842	871	899	927	955	972	983	989	990	985	974	959	937	927	911	892	
868	840	807	770	729	697	666	636	607	580	553	528	503	477	452	429	408	388	370	353	338	325	312	299	287	
184	115	81	73	65	58	53	49	42	37	32	28	24	21	18	16	14	12	10	9	8	7	6	5	4	
4	3	3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16E , SUBRUN 1 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	15	32	49	67	85	104	123	143	223	295	362	421	474	521	560	594	618	642	
665	689	713	737	761	785	821	854	883	910	934	954	972	987	990	989	985	977	966	951	932	910	887	863	839	
814	789	763	736	709	686	662	638	613	587	561	535	507	481	456	433	412	392	374	359	344	330	316	303	290	
180	110	80	76	65	57	50	45	39	33	29	25	21	19	16	14	12	10	9	7	6	5	5	4	3	
3	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

RUN 16E , SUBRUN 2 , DT= 0.05SECS(1ST 4 LINES) THEN 0.50SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	5	14	24	38	69	103	140	180	223	270	319	371	418	467	
518	571	625	681	739	799	830	857	882	904	923	938	951	961	974	984	989	990	986	979	967	951	927	903	879	
856	834	812	791	771	746	721	694	666	637	606	575	542	517	493	470	447	425	403	382	361	347	334	321	308	
200	126	87	75	63	52	43	35	31	26	23	20	17	15	13	11	9	8	7	6	5	4	4	3	3	
2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Table A3 (continued)

RUN 20B , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	28	44	61	80	100	121	144	167	192
219	247	275	306	337	370	404	440	476	514	532	550	567	585	603	620	638	656	673	691	709	726	744	762	779
797	815	833	850	868	885	901	915	928	940	951	960	968	975	980	985	988	989	990	989	986	983	978	972	964
868	755	707	578	482	402	321	273	225	192	168	146	127	110	96	84	75	69	65	64	61	57	54	51	48
45	41	38	35	32	30	28	26	24	23	22	20	19	18	17	16	15	14	13	12	11	11	10	9	9

RUN 20B , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	18	30	44	61	79	100	123	148	175
204	236	269	305	343	382	424	469	515	563	585	605	626	647	667	687	706	726	745	764	783	801	819	837	855
872	889	906	923	939	949	958	966	973	978	983	986	988	990	989	988	986	982	978	972	965	957	948	938	927
814	714	588	513	426	350	300	263	213	187	165	146	128	113	100	89	80	74	70	68	64	60	56	53	50
47	44	41	39	37	35	33	31	29	27	25	24	22	21	20	18	17	16	15	14	13	12	12	11	10

RUN 20C , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	3	5	7	9	12	15	18	22	26	37	49	61	74	87	100	114	128	143	158
173	189	205	221	238	256	273	292	310	329	360	391	421	451	480	509	537	565	592	619	645	671	696	720	744
768	790	813	835	856	873	889	904	918	930	941	952	960	968	975	980	984	987	989	990	989	987	984	980	975
896	777	685	606	513	434	368	303	263	224	198	174	153	134	118	104	93	83	76	72	67	63	59	56	52
49	46	44	41	39	36	34	32	29	27	26	24	22	21	19	18	17	16	14	13	13	12	11	10	9

RUN 20C , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	2	6	10	14	19	25	31	38	45	53	91	127	163	197	229	260	290	318	345	371
395	417	439	458	477	494	509	523	536	548	564	581	599	616	634	651	669	688	706	724	743	762	781	800	819
839	859	878	899	919	922	926	929	933	936	940	944	947	951	954	958	961	965	968	972	975	979	982	986	990
901	848	707	618	512	424	353	300	247	212	187	165	146	129	114	102	93	86	81	79	76	72	68	65	61
58	54	51	47	44	41	38	35	33	31	29	27	25	23	22	20	19	17	16	15	14	13	12	11	11

RUN 20D , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	3	4	6	7	9	11	14	16	40	65	90	116	142	168	196	223	251	280
309	339	369	399	431	462	494	527	560	593	610	626	643	659	676	692	709	725	742	758	775	791	808	824	841
857	874	890	907	923	937	949	959	968	975	981	985	988	990	989	988	985	980	974	967	958	947	935	922	907
824	742	610	527	445	379	329	263	230	197	172	150	130	113	98	87	77	71	67	65	62	59	56	52	49
46	42	39	36	32	30	28	26	25	23	21	20	18	17	16	15	14	13	12	11	10	10	9	8	8

RUN 20D , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	10	16	23	32	42	53	65	79
94	110	127	146	166	187	210	234	259	285	329	372	413	452	489	525	558	591	621	650	676	702	725	747	766
785	801	816	829	840	858	874	890	904	917	929	940	950	959	967	973	979	983	986	988	990	989	988	986	983
935	840	776	650	554	475	396	301	269	221	194	169	146	127	110	97	86	78	73	71	65	60	56	51	47
43	40	37	34	31	29	27	25	24	22	20	19	18	16	15	14	13	12	12	11	10	9	9	8	7

RUN 20E , SUBRUN 1 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	14	28	44	64
86	111	140	171	205	241	281	324	369	418	453	488	521	553	584	614	643	671	698	723	748	771	793	814	834
852	870	887	902	916	925	934	942	950	956	962	968	973	977	980	983	986	987	988	989	988	987	986	983	980
964	820	723	643	514	434	369	305	257	225	196	171	148	129	112	98	87	79	74	72	66	61	56	52	48
44	40	37	34	32	30	28	26	24	22	21	19	18	17	16	15	14	13	12	11	10	9	9	8	8

RUN 20E , SUBRUN 2 , DT= 0.02SECS(1ST 4 LINES) THEN 0.20SECS(LAST 2 LINES)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	31	62	94	127	159	192	226	260	295	329
365	400	436	473	510	547	585	623	662	701	715	729	742	755	768	780	791	803	814	824	834	844	853	862	871
879	886	894	900	907	921	935	947	957	966	974	980	984	987	989	990	988	986	982	976	969	961	951	940	927
845	721	597	577	474	391	329	288	247	185	162	141	122	106	92	81	72	66	63	61	56	52	48	44	41
38	35	33	32	30	28	26	25	23	21	20	19	17	16	15	14	13	12	11	10	10	9	8	8	7

Table A4: U-functions for drying air R.T.D.

RUN 1A SUBRUN 1 ,S=0 TO .2938E+00
-UO= 0.00000 0.89000 1.69800 2.43420 3.11330 3.74780 4.34790 4.92200 5.47500 6.01300 6.53900
U1= 31.79000 28.83000 26.20000 24.02000 22.29000 20.96000 19.94000 19.16000 18.56000 18.08000 17.70000
U2=103.90000 96.17000 82.25000 66.33000 51.61000 39.51000 30.20000 23.25000 18.13000 14.35000 11.54000

RUN 1A SUBRUN 2 ,S=0 TO .2553E+00
-UO= 0.00000 0.84900 2.32600 2.34000 3.00350 3.62580 4.21490 4.77700 5.31600 5.83600 6.34100
U1= 34.82000 31.77000 29.12000 26.92000 25.13000 23.68000 22.51000 21.54000 20.73000 20.05000 19.47000
U2=125.20000112.20000 95.07000 77.87000 62.93000 50.92000 41.60000 34.44000 28.89000 24.54000 21.05000

RUN 1B SUBRUN 1 ,S=0 TO .3327E+00
-UO= 0.00000 0.89900 1.71300 2.45310 3.13230 3.76170 4.35100 4.90700 5.43600 5.94100 6.42700
U1= 28.35000 25.69000 23.30000 21.27000 19.61000 18.27000 17.18000 16.28000 15.53000 14.89000 14.34000
U2= 82.39000 76.77000 66.59000 55.16000 44.76000 36.27000 29.70000 24.67000 20.81000 17.78000 15.35000

RUN 1C SUBRUN 1 ,S=0 TO .3318E+00
-UO= 0.00000 0.90200 1.72100 2.46600 3.15030 3.78500 4.37970 4.94200 5.47700 5.99000 6.48500
U1= 28.52000 25.88000 23.50000 21.48000 19.82000 18.48000 17.40000 16.51000 15.78000 15.16000 14.64000
U2= 81.55000 76.40000 66.61000 55.33000 44.86000 0.36190 29.41000 24.20000 20.20000 17.09000 14.64000

RUN 1D SUBRUN 1 ,S=0 TO .4144E+00
-UO= 0.00000 0.91000 1.72200 2.44750 3.10300 3.70450 4.26500 4.79400 5.29900 5.78400 6.25400
U1= 23.21000 20.74000 18.48000 16.59000 15.11000 13.97000 13.11000 12.45000 11.93000 11.52000 11.18000
U2= 60.08000 57.95000 50.44000 40.64000 31.31000 23.75000 18.11000 14.05000 11.14000 9.03700 7.49300

RUN 1E SUBRUN ,S=0 TO .4431E+00
-UO= 0.00000 0.89500 1.69700 2.41570 3.06770 3.66660 4.22400 4.74900 5.24800 5.72600 6.18700
U1= 21.31000 19.11000 17.10000 15.41000 14.07000 13.01000 12.19000 11.53000 11.01000 10.58000 10.22000
U2= 50.63000 48.20000 41.91000 34.16000 26.90000 20.98000 16.48000 13.14000 10.66000 8.79900 7.37200

RUN 1E SUBRUN 2 ,S=0 TO .4097E+00
-UO= 0.00000 0.94600 1.80000 2.56920 3.26470 3.89900 4.48300 5.02700 5.53700 6.02000 6.48000
U1= 24.23000 21.95000 19.77000 17.83000 16.18000 14.83000 13.73000 12.84000 12.10000 11.49000 10.98000
U2= 55.21000 55.13000 50.77000 43.88000 36.43000 29.70000 24.14000 19.74000 16.30000 13.60000 11.47000

RUN 2A SUBRUN 1 ,S=0 TO .2938E+00
-UO= 0.00000 0.89000 1.69800 2.43420 3.11330 3.74780 4.34790 4.92200 5.47500 6.01300 6.53900
U1= 31.79000 28.83000 26.20000 24.02000 22.29000 20.96000 19.94000 19.16000 18.56000 18.08000 17.70000
U2=103.90000 96.17000 82.25000 66.33000 51.61000 39.51000 30.20000 23.25000 18.13000 14.35000 11.54000

RUN 2A SUBRUN 2 ,S=0 TO .2553E+00
-UO= 0.00000 0.84900 1.62600 2.34000 3.00350 3.62580 4.21490 4.77700 5.31600 5.83600 6.34100
U1= 34.82000 31.77000 29.12000 26.92000 25.13000 23.68000 22.51000 21.54000 20.73000 20.05000 19.47000
U2=125.20000112.20000 95.07000 77.87000 62.93000 50.92000 41.60000 34.44000 28.89000 24.54000 21.05000

RUN 2B SUBRUN 1 ,S=0 TO .3738E+00
-UO= 0.00000 0.92300 1.75300 2.50290 3.18570 3.81570 4.40400 4.96000 5.49000 5.99800 6.48800
U1= 25.99000 23.42000 21.07000 19.09000 17.50000 16.25000 15.27000 14.49000 13.86000 13.34000 12.90000
U2= 69.61000 66.63000 58.22000 47.65000 37.66000 29.49000 18.67000 15.27000 12.71000 10.75000 0.00000

RUN 2C SUBRUN 1 ,S=0 TO .3784E+00
-UO= 0.00000 0.92700 1.76000 2.51180 3.19470 3.82300 4.40800 4.95900 5.48300 5.98500 6.46800
U1= 25.75000 23.23000 20.89000 18.89000 17.26000 15.98000 14.98000 14.18000 13.53000 13.01000 12.56000
U2= 67.12000 65.16000 57.76000 47.85000 38.10000 29.92000 23.59000 18.86000 15.34000 12.70000 10.69000

RUN 2C SUBRUN 2 ,S=0 TO .3274E+00
-UO= 0.00000 0.90900 1.73700 2.49210 3.18700 3.83270 4.43800 5.01200 5.55800 6.08200 6.58600
U1= 29.10000 26.49000 24.11000 22.09000 20.42000 19.07000 17.97000 17.07000 16.32000 15.68000 15.13000
U2= 81.56000 76.90000 67.45000 56.29000 45.79000 37.05000 30.22000 25.01000 21.06000 18.03000 15.67000

RUN 2D SUBRUN 1 ,S=0 TO .3555E+00
-UO= 0.00000 0.90800 1.72800 2.46980 3.14610 3.76800 4.34600 4.88700 5.39700 5.88000 6.33900
U1= 26.84000 24.26000 21.91000 19.89000 18.21000 16.84000 15.71000 14.75000 13.94000 13.23000 12.61000
U2= 73.97000 70.20000 61.81000 51.83000 42.57000 34.98000 29.12000 24.68000 21.27000 18.58000 16.40000

RUN 2D SUBRUN 2 ,S=0 TO .4146E+00
-UO= 0.00000 0.90500 1.71300 2.43470 3.08250 3.66870 4.20300 4.69400 5.14800 5.57000 5.96300
U1= 23.01000 20.63000 18.40000 16.46000 14.84000 13.48000 12.34000 11.37000 10.54000 9.81200 9.17900
U2= 57.99000 56.29000 50.47000 42.95000 35.78000 29.85000 25.23000 21.65000 18.76000 16.34000 14.23000

RUN 2E SUBRUN 1 ,S=0 TO .3776E+00
-UO= 0.00000 0.90000 1.71000 2.44160 3.10990 3.72760 4.30600 4.85200 5.37400 5.87500 6.35800
U1= 25.08000 22.60000 20.36000 18.48000 16.98000 15.80000 14.87000 14.12000 13.52000 13.02000 12.60000
U2= 67.26000 63.39000 54.81000 44.63000 35.25000 27.65000 21.89000 17.62000 14.45000 12.06000 10.23000

RUN 2E SUBRUN 2 ,S=0 TO .3815E+00
-UO= 0.00000 0.89200 1.69500 2.41990 3.08090 3.69100 4.26100 4.79800 5.30800 5.79700 6.26700
U1= 24.63000 22.17000 19.96000 18.11000 16.61000 15.42000 14.48000 13.71000 13.08000 12.56000 12.11000
U2= 66.15000 61.95000 53.50000 43.77000 34.88000 27.70000 22.21000 18.10000 15.01000 12.66000 10.83000

RUN 3A SUBRUN 1 ,S=0 TO .2889E+00
-UO= 0.00000 0.78600 1.50400 2.16950 2.79460 3.38830 3.95800 4.50700 5.04100 3.15010 6.07300
U1= 28.51000 25.93000 23.88000 22.28000 21.05000 20.09000 19.34000 18.74000 18.25000 17.85000 17.51000
U2= 98.28000 80.14000 62.71000 48.33000 37.34000 29.18000 23.16000 18.68000 15.29000 12.69000 10.66000

RUN 4A SUBRUN 1 ,S=0 TO .4611E+00
-UO= 0.00000 0.75200 1.42730 2.04550 2.62070 3.16330 3.68100 4.17800 4.65900 5.12600 5.58200
U1= 17.26000 15.41000 13.97000 12.90000 12.09000 11.47000 10.99000 10.60000 10.27000 9.99800 9.76100
U2= 44.70000 35.55000 26.90000 20.09000 15.18000 11.77000 9.38000 7.68300 6.44500 5.51700 4.80500

Table A4 (continued)

RUN 5A SUBRUN ,S=0 TO .4859E+00
-U0= 0.00000 0.75400 1.43700 2.06700 2.65650 3.21510 3.74950 4.26500 4.76500 5.25100 5.72800
U1= 16.36000 14.72000 13.46000 12.51000 11.79000 11.23000 10.79000 10.43000 10.14000 9.90400 9.70000
U2= 37.67000 29.61000 22.49000 17.00000 13.00000 10.14000 8.07400 6.55600 5.41500 4.54000 3.85600

RUN 5B SUBRUN ,S=0 TO .6069E+00
-U0= 0.00000 0.80600 1.51300 2.15640 2.73890 3.27900 3.78700 4.27000 4.73300 5.18000 5.61500
U1= 14.16000 12.45000 11.07000 10.01000 9.21600 8.61100 8.14600 7.78200 7.49200 7.25600 7.06100
U2= 30.46000 25.51000 19.94000 15.11000 11.39000 8.68900 6.74300 5.33200 4.29300 3.51400 2.92100

RUN 5C SUBRUN ,S=0 TO .6057E+00
-U0= 0.00000 0.81100 1.52500 2.16110 2.73930 3.27350 3.77360 4.24700 4.69800 5.13100 5.54300
U1= 14.31000 12.52000 11.08000 9.98300 9.15100 8.51500 8.01700 7.61700 7.28800 7.01200 6.77700
U2= 31.87000 26.73000 20.83000 15.75000 11.94000 9.22700 7.32000 5.95600 4.95300 4.19400 3.60300

RUN 5D SUBRUN ,S=0 TO .5680E+00
-U0= 0.00000 0.81200 1.52900 2.17060 2.75510 3.29610 3.80300 4.28400 4.74200 5.18300 5.60800
U1= 15.25000 13.40000 11.90000 10.75000 9.87400 9.20400 8.67800 8.25500 7.90600 7.61300 7.36100
U2= 35.30000 29.66000 23.19000 17.61000 13.39000 10.38000 8.25100 6.72700 5.60900 4.76700 4.11700

RUN 5E SUBRUN ,S=0 TO .6224E+00
-U0= 0.00000 0.82500 1.54700 2.18760 2.76800 3.30320 3.80420 4.27900 4.73200 5.16800 5.59000
U1= 14.19000 12.37000 10.89000 9.76400 8.92700 8.29900 7.81900 7.44100 7.13700 6.88600 6.67600
U2= 31.47000 26.70000 20.79000 15.55000 11.58000 8.76200 6.79700 5.41100 4.41300 3.67500 3.11600

RUN 6A SUBRUN 1 ,S=0 TO .5009E+00
-U0= 0.00000 0.70500 1.35120 1.95100 2.51520 3.05150 3.56500 4.06100 4.54200 5.01000 5.46800
U1= 14.79000 13.44000 12.39000 11.59000 10.96000 10.47000 10.07000 9.74000 9.46700 9.23600 9.03800
U2= 30.30000 23.66000 18.21900 14.09000 11.07000 8.84700 7.20200 5.95900 5.00300 4.25600 3.66300

RUN 6A SUBRUN 2 ,S=0 TO .4475E+00
-U0= 0.00000 0.68100 1.30900 1.89670 2.45210 2.98120 3.48800 3.97700 4.44900 4.90600 5.35100
U1= 15.90000 14.57000 13.55000 12.74000 12.10000 11.57000 11.11000 10.72000 10.38000 10.07000 9.79600
U2= 33.80000 26.01000 20.14000 15.97000 13.03000 10.93000 9.36800 8.17700 7.23700 6.47200 5.83300

RUN 6B SUBRUN 1 ,S=0 TO .5186E+00
-U0= 0.00000 0.77600 1.47150 2.10180 2.68070 3.21900 3.72400 4.20300 4.65900 5.09600 5.61600
U1= 15.86000 14.14000 12.73000 11.62000 10.74000 10.04000 9.47200 8.99900 8.59800 8.25300 7.95200
U2= 35.98000 30.14000 24.12000 19.00000 15.05000 12.12000 9.96600 8.36100 7.14400 6.20000 5.45200

RUN 6B SUBRUN 2 ,S=0 TO .5899E+00
-U0= 0.00000 0.77000 1.45400 2.07160 2.63690 3.16240 3.65700 4.12700 4.57600 2.72040 5.42900
U1= 13.88000 12.28000 10.98000 9.98400 9.21700 8.62400 8.15700 7.78200 7.47600 7.22200 7.00900
U2= 29.72000 24.62000 19.29000 14.80000 11.38000 8.87500 7.05500 5.71300 4.70600 3.93300 3.33100

RUN 6C SUBRUN 1 ,S=0 TO .5276E+00
-U0= 0.00000 0.73500 1.39100 1.98790 2.53880 3.05380 3.54000 4.00200 4.44400 4.86700 5.27400
U1= 14.79000 13.12000 11.83000 10.84000 10.08000 9.47100 8.97600 8.55600 8.19100 7.86600 7.57300
U2= 35.19000 27.97000 21.38000 0.16340 12.77000 10.30000 8.59300 7.38300 6.50000 5.83300 5.31200

RUN 6C SUBRUN 2 ,S=0 TO .6110E+00
-U0= 0.00000 0.77900 1.46900 2.08840 2.65340 3.17650 3.66700 4.13000 4.57200 4.99600 5.40400
U1= 13.59000 11.97000 10.66000 9.65300 8.87600 8.27100 7.79000 7.39900 7.07300 0.67980 6.56200
U2= 28.85000 24.01000 18.83000 14.46000 11.16000 8.77400 1.05900 5.80900 4.87600 4.16300 3.60500

RUN 6D SUBRUN 1 ,S=0 TO .6536E+00
-U0= 0.00000 0.77600 1.45560 2.05700 2.59760 3.09060 3.54500 3.96900 4.36600 4.74000 5.09400
U1= 12.72000 11.09000 9.74700 8.69700 7.87800 7.23000 6.70200 6.26300 5.89000 5.56800 5.28800
U2= 26.98000 22.86000 18.17000 14.13000 11.08000 8.89100 7.32500 6.17200 5.28800 4.58000 3.99200

RUN 6D SUBRUN 2 ,S=0 TO .5863E+00
-U0= 0.00000 0.76800 1.44900 2.06310 2.62500 3.14670 3.63700 4.10100 4.54400 4.96900 5.38000
U1= 13.93000 12.30000 11.00000 9.99000 9.21300 8.60700 8.12300 7.72800 7.39900 7.12100 6.88300
U2= 30.35000 25.02000 19.55000 15.02000 11.63000 9.18700 7.42000 6.11900 5.13600 4.37300 3.76700

RUN 6E SUBRUN 1 ,S=0 TO .6771E+00
-U0= 0.00000 0.80300 1.50200 2.11970 2.67640 1.92190 3.66600 4.11700 4.54800 4.96200 5.36200
U1= 12.73000 11.04000 9.66400 8.62500 7.85700 7.28400 6.84700 6.50400 6.23000 6.00600 5.81900
U2= 26.96000 22.84000 17.69000 13.15000 9.73800 7.33900 5.67300 4.49800 3.64700 3.01500 2.53200

RUN 6E SUBRUN 2 ,S=0 TO .6128E+00
-U0= 0.00000 0.78400 1.47500 2.09410 2.65890 3.18280 3.67500 4.14300 4.59200 5.02400 5.44300
U1= 13.65000 11.98000 10.64000 9.61600 8.85100 8.27200 7.82300 7.46600 7.17600 6.93500 6.73200
U2= 29.58000 24.65000 19.10000 14.36000 10.80000 8.26900 6.48800 5.21800 4.29200 3.59900 3.06800

RUN 7A SUBRUN ,S=0 TO .5659E+00
-U0= 0.00000 0.65300 1.25000 1.80500 2.32880 2.82810 3.30760 3.77100 4.21900 4.65600 5.08200
U1= 12.17000 10.99000 1.01400 9.50900 9.02300 8.63600 8.31800 8.05000 7.82100 7.62100 7.44600
U2= 24.44000 17.59000 12.84000 9.69200 7.60000 6.16300 5.13300 4.36500 3.77100 3.29900 2.91300

RUN 8A SUBRUN ,S=0 TO .6751E+00
-U0= 0.00000 0.61100 1.17200 1.69470 2.18860 2.65970 3.11200 3.54900 3.97200 4.38400 4.78600
U1= 9.53100 8.64200 7.99600 7.51200 7.13500 6.83100 6.57900 6.36600 6.18300 6.02400 5.88400
U2= 0.15430 0.11140 0.82070 0.62740 0.49780 0.40740 0.34140 0.29130 0.25200 0.22040 0.19460

RUN 9A SUBRUN 1 ,S=0 TO .7567E+00
-U0= 0.00000 0.63900 1.21240 1.73840 2.22940 2.69140 3.13240 3.55440 3.96240 4.35740 4.74140
U1= 8.96600 7.96300 7.22900 6.68600 6.27300 5.94900 5.68800 5.47200 5.29200 5.13900 5.00800
U2= 15.36000 11.30000 8.27500 6.20100 4.79600 3.82100 3.11800 2.59200 2.18400 1.86000 1.59800

Table A4 (continued)

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RUN  9A SUBRUN 2 ,S=0 TO  .7517E+00
-U0=  0.00000  0.64840  1.23160  1.76640  2.26540  2.73740  3.18740  3.62040  4.03940  4.44640  4.84340
 U1=  9.14600  8.14300  7.40000  6.85000  6.43500  6.11400  5.85900  5.65200  5.48100  5.33800  5.21500
 U2= 15.33000 11.47000  8.45600  6.31000  4.82100  3.78000  3.03400  2.48600  2.07200  1.75300  1.50000

RUN  9B SUBRUN 1 ,S=0 TO  .6457E+00
-U0=  0.00000  0.59340  1.14430  1.66510  2.16410  2.64510  3.11210  3.56610  4.00910  4.44310  4.86810
 U1=  0.96070  0.88140  0.82700  0.78750  0.75720  0.73260  0.71190  0.69390  0.67800  0.66370  0.65080
 U2= 14.88000 10.05000  7.07500  5.28800  4.18500  3.46700  2.97000  2.60600  2.32500  2.10000  1.91400

RUN  9B SUBRUN 2 ,S=0 TO  .6778E+00
-U0=  0.00000  0.59640  1.14740  1.66340  2.15340  2.62240  3.07240  3.50740  3.92840  4.33740  4.73640
 U1=  9.20800  8.42200  7.84500  7.40400  7.05200  6.76100  6.51500  6.30200  6.11600  5.95200  5.80700
 U2= 13.63000  9.83000  7.35600  5.75900  4.69000  3.93300  3.36700  2.92400  2.56500  2.26900  2.01900

RUN  9C SUBRUN 1 ,S=0 TO  .7407E+00
-U0=  0.00000  0.64880  1.23280  1.76920  2.27120  2.74620  3.20020  3.63720  4.06120  4.47320  4.87520
 U1=  9.28900  8.27100  7.52500  6.97900  6.57000  6.25500  6.00400  5.79900  5.62700  5.48000  5.35300
 U2= 15.86000 11.75000  8.56200  6.32700  4.80700  3.76700  3.04000  2.51700  2.13000  1.83400  1.60200

RUN  9C SUBRUN 2 ,S=0 TO  .7822E+00
-U0=  0.00000  0.66610  1.25670  1.79150  2.28540  2.74840  3.18740  3.60740  4.01140  4.40340  4.78440
 U1=  9.09300  7.97900  7.15000  6.54200  6.09000  5.74600  5.47500  5.25700  5.07600  4.92400  4.79300
 U2= 16.23000 12.31000  9.03400  6.64700  5.00000  3.87200  3.08600  2.52300  2.10800  1.79400  1.54900

RUN  9D SUBRUN 1 ,S=0 TO  .7916E+00
-U0=  0.00000  0.67150  1.26530  1.80190  2.29790  2.76190  3.20190  3.62290  4.02890  4.42290  4.80590
 U1=  9.06900  7.93700  7.09700  6.48600  6.03400  5.69100  5.42500  5.21200  5.03800  4.89300  4.77100
 U2= 16.32000 12.34000  9.00900  6.59100  4.92500  3.78300  2.98600  2.41500  1.99300  1.67400  1.42700

RUN  9D SUBRUN 2 ,S=0 TO  .7980E+00
-U0=  0.00000  0.67480  1.26810  1.80210  2.29010  2.74410  3.17010  3.57510  3.96210  4.33310  4.69110
 U1=  9.05700  7.89400  7.01700  6.36600  5.87600  5.49700  5.19400  4.94600  4.73600  4.55700  4.40100
 U2= 16.49000 12.69000  9.42200  7.02000  5.35600  4.21400  3.41500  2.84100  2.41300  2.08500  1.82500

RUN  9E SUBRUN 1 ,S=0 TO  .8444E+00
-U0=  0.00000  0.68010  1.27360  1.80450  2.29050  2.74350  3.17150  3.58050  3.97350  4.35350  4.72250
 U1=  8.67100  7.48200  6.60900  5.98500  5.53400  5.19800  4.93800  4.73200  4.56400  4.42400  4.30500
 U2= 16.05000 12.12000  8.69600  6.22500  4.56700  3.46500  2.71700  2.19000  1.80700  1.51800  1.29500

RUN  9E SUBRUN 2 ,S=0 TO  .8353E+00
-U0=  0.00000  0.67660  1.26930  1.80130  2.29030  2.74830  3.18130  3.59530  3.99530  4.38230  4.75930
 U1=  8.70300  7.53900  6.68700  6.07800  5.63700  5.31000  5.05800  4.85900  4.69600  4.56100  4.44600
 U2= 15.90000 11.96000  8.58700  6.14900  4.50400  3.40600  2.66000  2.13800  1.76000  1.47900  1.26300

RUN 10A SUBRUN 1 ,S=0 TO  .9380E+00
-U0=  0.00000  0.63500  1.20660  1.73350  2.22910  2.70200  3.15700  3.59800  4.02800  4.44900  4.86200
 U1=  7.21100  6.39000  5.82500  5.43200  5.14900  4.93800  4.77300  1.64100  4.53200  4.44000  4.36100
 U2= 10.44000  7.22700  4.97200  3.51300  2.58200  1.97400  1.56300  1.27300  1.06300  0.90390  0.78120

RUN 10A SUBRUN 2 ,S=0 TO  .9455E+00
-U0=  0.00000  0.65800  1.23920  1.76680  2.25640  2.71870  3.16100  3.58700  4.00100  4.40500  4.80100
 U1=  7.46200  6.51000  5.83200  5.35600  5.01900  4.77200  4.58500  4.44000  4.32400  4.22900  4.14900
 U2= 11.70000  8.50900  5.96800  4.20000  3.02800  2.25200  1.72800  1.36500  1.10500  0.91510  0.77250

RUN 10B SUBRUN 1 ,S=0 TO  .8120E+00
-U0=  0.00000  0.58600  1.12560  1.63310  2.11620  2.57980  3.02800  3.46200  3.88500  4.29700  4.70100
 U1=  7.56700  6.89700  6.43000  6.08600  5.82100  5.60600  5.42700  5.27300  5.14000  5.02300  4.92000
 U2=  9.92400  6.80800  4.86900  3.67800  2.91800  2.40400  2.03400  1.75300  1.53200  1.35200  1.20300

RUN 10B SUBRUN 2 ,S=0 TO  .8042E+00
-U0=  0.00000  0.57300  1.10660  1.61190  2.09640  2.56460  3.01900  3.46200  3.89500  4.31900  4.73400
 U1=  7.45300  6.84700  6.43800  6.14300  5.91600  5.73200  5.57600  5.44100  5.32300  5.21800  5.12300
 U2=  9.24500  6.09600  6.24900  3.17400  2.52000  2.09300  1.79300  1.56600  1.38500  1.23700  1.11100

RUN 10C SUBRUN 1 ,S=0 TO  .8876E+00
-U0=  0.00000  0.63700  1.20670  1.72910  2.21740  2.67990  3.12200  3.54900  3.96100  4.36200  4.75300
 U1=  7.64600  6.75300  6.12200  5.67400  5.34300  5.09000  4.88700  4.72100  4.58000  4.45800  4.35100
 U2= 11.84000  8.42400  5.93800  4.29300  3.22900  2.53100  2.05500  1.71800  1.47000  1.28000  1.13000

RUN 10C SUBRUN 2 ,S=0 TO  .8629E+00
-U0=  0.00000  0.63300  1.20030  1.72020  2.20590  2.66560  3.10500  3.52800  3.93700  4.33400  4.72200
 U1=  7.82100  6.91000  6.26800  5.80700  5.46400  5.20000  4.98900  4.81500  4.67000  4.54600  4.43900
 U2= 12.44000  8.82100  6.24600  4.55600  3.45700  2.72000  2.20600  1.83200  1.55000  1.33200  1.15800

RUN 10D SUBRUN 1 ,S=0 TO  .1057E+01
-U0=  0.00000  0.66800  1.24090  1.74880  2.21140  2.64180  3.04900  3.43800  3.81300  4.17600  4.53000
 U1=  6.86800  5.82000  5.07800  4.56700  4.20900  3.95200  3.75900  3.60900  3.49000  3.39300  3.31200
 U2= 11.46000  8.38200  5.79800  4.00500  2.84200  2.09100  1.59400  1.25300  1.01200  0.83510  0.70250

RUN 10D SUBRUN 2 ,S=0 TO  .1093E+01
-U0=  0.00000  0.66830  1.23730  1.73540  2.18290  2.59360  2.97600  3.33800  3.68200  4.01200  4.33000
 U1=  6.66900  5.61200  4.84400  4.30000  3.90900  3.61900  3.39700  3.32200  3.08000  2.96400  2.86600
 U2= 11.07000  8.27800  5.88100  4.18200  3.05300  2.30400  1.79300  1.43300  1.17000  0.97360  0.82290

RUN 10E SUBRUN 1 ,S=0 TO  .9659E+00
-U0=  0.00000  0.67100  1.25380  1.77460  2.25120  2.69540  3.11500  3.51600  3.90000  4.27200  4.53600
 U1=  7.50100  6.44000  5.67700  5.13800  4.75000  4.46200  4.23800  4.05900  3.91100  3.78600  3.67800
 U2= 12.67000  9.33600  6.59700  4.68700  3.43000  2.60700  2.05500  1.67300  1.40000  1.20000  1.04800
```

Table A4 (continued)

RUN 10E SUBRUN 2 ,S=0 TO .1154E+01

-U0=	0.00000	0.67200	1.24000	1.73510	2.18020	2.59020	2.97400	3.33900	3.68900	4.02600	4.35300
U1=	6.37800	5.31900	4.56500	4.04800	3.68800	3.43000	3.23800	3.09000	2.97100	2.87500	2.79400
U2=	10.54000	7.79200	5.38700	3.70100	2.61000	1.91100	1.45200	1.14000	0.92070	0.76120	0.64200

RUN 11A SUBRUN ,S=0 TO .8529E+00

-U0=	0.00000	0.59100	1.13330	1.64030	2.12190	2.58410	3.03100	3.46400	3.88700	4.30100	4.70600
U1=	7.31300	6.60900	6.12600	5.78100	5.52400	5.32100	5.15700	5.01800	4.90000	4.79600	4.70400
U2=	9.94300	6.77200	4.72500	3.45300	2.65100	2.12400	1.76000	1.49700	1.29800	1.14300	1.01900

RUN 13A SUBRUN ,S=0 TO .1186E+01

-U0=	0.00000	0.56250	1.07100	1.54190	1.98520	2.40710	2.81200	3.18200	3.58100	3.94900	4.30900
U1=	5.03700	4.48500	4.11000	3.84200	3.63900	3.47900	3.34800	3.23900	3.14600	3.06600	2.99600
U2=	5.66900	3.78100	2.63400	1.94300	1.50600	1.21200	1.00200	0.84560	0.72520	0.63050	0.55460

RUN 14A SUBRUN 1 ,S=0 TO .1433E+01

-U0=	0.00000	0.56400	1.07520	1.55410	2.01040	2.45010	2.87700	3.29200	3.69900	4.09700	4.48900
U1=	4.17800	3.72300	3.44100	3.25500	3.12200	3.02000	2.93700	2.86800	2.80800	2.75700	2.71100
U2=	4.03200	2.45700	1.56600	1.08000	0.80490	0.63670	0.52510	0.44530	0.38470	0.33670	0.29750

RUN 14A SUBRUN 2 ,S=0 TO .1590E+01

-U0=	0.00000	0.57320	1.06860	1.50660	1.89690	2.24330	2.54700	2.80900	3.03100	3.21600	3.36900
U1=	3.91500	3.33000	2.92000	2.59800	2.31400	2.04400	1.77800	1.52000	1.27600	1.05600	0.86480
U2=	4.43200	3.02400	2.23100	1.86600	1.72800	1.68500	1.65300	1.58600	1.46500	1.29900	1.10600

RUN 14B SUBRUN 1 ,S=0 TO .1248E+01

-U0=	0.00000	0.55000	1.06800	1.56670	2.05220	2.52800	2.99610	3.45800	3.91300	4.36300	4.80800
U1=	4.56900	4.25700	4.06100	3.93700	3.85000	3.78100	3.72400	3.67400	3.62800	3.58500	3.54500
U2=	3.57400	2.01600	1.21800	0.81690	0.60930	0.45940	0.42790	0.38440	0.35390	0.33070	0.31210

RUN 14B SUBRUN 2 ,S=0 TO .1214E+01

-U0=	0.00000	0.56400	1.08700	1.58610	2.06860	2.48550	3.00090	3.45400	3.90000	4.33900	4.77200
U1=	4.89200	4.44900	4.19400	4.03500	3.92400	3.83800	3.76700	3.70300	3.64600	3.59200	3.54100
U2=	4.80200	2.71100	1.61600	1.06700	0.78790	0.63780	0.55070	0.49580	0.45820	0.43060	0.40950

RUN 14C SUBRUN 1 ,S=0 TO .1244E+01

-U0=	0.00000	0.54200	1.05500	1.54990	2.03020	2.49860	2.95570	3.40100	3.83400	4.25100	4.65100
U1=	4.51600	4.22400	4.04200	3.91400	3.81200	3.72000	3.62900	3.53100	3.42100	3.29100	3.13000
U2=	3.03400	1.80600	1.19100	0.89620	0.76600	0.72670	0.74850	0.82380	0.95700	1.15800	1.43500

RUN 14C SUBRUN 2 ,S=0 TO .1304E+01

-U0=	0.00000	0.52900	1.03650	1.52990	2.01260	2.48640	2.95300	3.41200	3.86400	4.31100	4.75200
U1=	4.16800	3.96200	3.83200	3.73900	3.66500	3.60300	3.54700	3.49500	3.44700	3.40300	3.36100
U2=	2.02500	1.22200	0.82350	0.62280	0.51540	0.45230	0.41050	0.37920	0.35330	0.33040	0.30950

RUN 14D SUBRUN 1 ,S=0 TO .1295E+01

-U0=	0.00000	0.53600	1.04680	1.54100	2.02330	2.49580	2.96000	3.41700	3.86600	4.30900	4.74500
U1=	4.28300	4.02800	3.87300	3.78700	3.68500	3.61600	3.55500	3.49800	3.44400	3.39300	3.34400
U2=	2.57100	1.49400	0.96360	0.70360	0.57130	0.49900	0.45520	0.42560	0.40340	0.38520	0.36940

RUN 14D SUBRUN 2 ,S=0 TO .1351E+01

-U0=	0.00000	0.55200	1.06950	1.56730	2.05230	2.52770	2.99500	3.45500	3.90800	4.35500	4.79600
U1=	4.27900	3.93200	3.74600	3.63300	3.55300	3.48900	3.43200	3.38000	3.33200	3.28500	3.24100
U2=	3.51600	1.82300	1.03400	0.68140	0.52040	0.44170	0.39860	0.37130	0.35110	0.33410	0.31880

RUN 14E SUBRUN 1 ,S=0 TO .1345E+01

-U0=	0.00000	0.54300	1.05050	1.53380	1.99960	2.45090	2.89000	3.31700	3.73400	4.14200	4.54100
U1=	4.22700	3.88400	3.67200	3.52400	3.40700	3.30700	3.21900	3.13900	3.06500	2.99800	2.93600
U2=	3.31000	1.95000	1.28500	0.96110	0.79270	0.69300	0.62420	0.56970	0.52240	0.47930	0.43910

RUN 14E SUBRUN 2 ,S=0 TO .1267E+01

-U0=	0.00000	0.54900	1.06060	1.54750	2.01570	2.46850	2.90700	3.33300	3.74700	4.14800	4.53700
U1=	4.53200	4.16400	3.93100	3.76400	3.63200	3.51800	3.41300	3.31300	3.21600	3.12000	3.02400
U2=	3.68600	2.25800	1.51800	1.14800	0.95930	0.85990	0.80550	0.77530	0.76020	0.75600	0.76110

RUN 15A SUBRUN ,S=0 TO .1447E+01

-U0=	0.00000	0.54570	1.04480	1.51310	1.95930	2.38900	2.80400	3.20900	3.60300	3.99000	4.36900
U1=	3.98200	3.58500	3.32900	3.15100	3.01900	2.91500	2.83000	2.75900	2.69700	2.64300	2.59600
U2=	3.42800	2.16400	1.44700	1.04200	0.80070	0.64520	0.53740	0.45790	0.39650	0.34750	0.30740

RUN 16A SUBRUN 1 ,S=0 TO .1513E+01

-U0=	0.00000	0.55960	1.07160	1.55350	2.01470	2.46000	2.89300	3.31500	3.72800	4.13300	4.53100
U1=	3.91000	3.51400	3.27000	3.10900	2.99100	2.89900	2.82300	2.75800	2.70100	2.65000	2.60400
U2=	3.34600	2.01200	1.28300	0.89380	0.67750	0.54760	0.46240	0.40170	0.35540	0.31820	0.28730

RUN 16A SUBRUN 2 ,S=0 TO .1563E+01

-U0=	0.00000	0.55770	1.06530	1.54110	1.99500	2.43200	2.85700	-0.62400	3.67400	4.07000	4.45900
U1=	3.78400	3.38100	3.13200	2.96700	2.84700	2.75300	2.67700	2.61300	2.55800	2.51000	2.46700
U2=	3.27800	1.98900	1.27300	0.88660	0.66800	0.53380	0.44400	0.37900	0.32900	0.28890	0.25570

RUN 16B SUBRUN 1 ,S=0 TO .1512E+01

-U0=	0.00000	5.62100	10.67600	15.35500	9.68200	10.10300	10.50800	10.90000	11.28000	11.65100	12.01400
U1=	3.96400	3.50400	3.20300	2.99600	2.84400	2.72700	2.63100	2.55200	2.48400	2.42500	2.37400
U2=	3.76700	2.42800	1.62200	1.15500	0.87460	0.69520	0.57250	0.48340	0.41580	0.36260	0.31960

RUN 16B SUBRUN 2 ,S=0 TO .1750E+01

-U0=	0.00000	0.55840	1.05970	1.52430	1.96410	2.38410	2.79110	3.18510	3.57010	3.94710	4.31610
U1=	3.41200	3.00300	2.74600	2.57500	2.45300	2.36100	2.28700	2.22600	2.17400	2.13100	2.09200
U2=	2.93700	1.82500	1.17500	0.81150	0.60020	0.46890	0.38090	0.31790	0.27050	0.23330	0.20330

Table A4 (continued)

RUN 16C SUBRUN 1 ,S=0 TO .1601E+01
-U0= 0.00000 0.54160 1.04390 1.51940 1.97550 2.41450 2.84050 3.25550 3.65950 4.05450 4.44150
U1= 3.54600 3.24200 3.04400 2.90200 2.79200 2.70200 2.62400 2.55500 2.49400 2.43900 2.39000
U2= 2.37300 1.50000 1.02600 0.76750 0.61740 0.52170 0.45440 0.40290 0.36110 0.32560 0.29480

RUN 16C SUBRUN 2 ,S=0 TO .1466E+01
-U0= 0.00000 0.54490 1.05550 1.54400 2.01660 2.47660 2.92660 3.36860 3.80160 4.22760 4.64760
U1= 3.87700 3.58100 3.39700 3.27200 3.17800 3.10300 3.03800 2.98200 2.93100 2.88500 2.84300
U2= 2.57700 1.55500 1.01100 0.72540 0.56760********** 0.41020 0.36440 0.32810 0.29780 0.27150

RUN 16D SUBRUN 1 ,S=0 TO .1484E+01
-U0= 0.00000 0.53390 1.04260 1.53520 2.01590 2.48790 2.95090 3.40590 3.85490 4.29590 4.73190
U1= 3.71600 3.49800 3.36600 3.27600 3.20600 3.14700 3.09400 3.04500 2.99800 2.95500 2.91300
U2= 1.92500 1.10900 0.71380 0.52310 0.42740 0.37540 0.34360 0.32130 0.30360 0.28830 0.27420

RUN 16D SUBRUN 2 ,S=0 TO .1483E+01
-U0= 0.00000 0.54710 1.06190 1.55640 2.03690 2.50490 2.96390 3.41290 3.85390 4.28590 4.71090
U1= 3.84300 3.56100 3.39300 3.28100 3.19600 3.12400 3.06000 3.00000 2.94300 2.88900 2.83800
U2= 2.48700 1.42800 0.90040 0.64530 0.51970 0.45410 0.41620 0.39100 0.37160 0.35500 0.33950

RUN 16E SUBRUN 1 ,S=0 TO .1532E+01
-U0= 0.00000 0.54530 1.05810 1.55060 2.02830 2.49530 2.95330 3.40230 3.84330 4.27630 4.70330
U1= 3.70900 3.43500 3.27200 3.16300 3.08200 3.01500 2.95600 2.90300 2.85400 2.80800 2.76600
U2= 2.34500 1.34200 0.84340 0.59970 0.47580 0.40680 0.36340 0.33220 0.30720 0.28560 0.26630

RUN 16E SUBRUN 1 ,S=0 TO .1545E+00
-U0= 0.00000 0.53430 1.03360 1.50820 1.96420 2.40520 2.83220 3.24720 3.65220 4.04820 4.43520
U1= 3.60700 3.33100 3.14500 3.00800 2.89900 2.80700 2.72700 2.65500 2.59100 2.53200 2.47900
U2= 2.22600 1.43400 1.01300 0.78160 0.64420 0.55410 0.48910 0.43860 0.39700 0.36160 0.33060

RUN 17A SUBRUN 1 ,S=0 TO .1779E+00
-U0= 0.00000 0.54190 1.03790 1.50490 1.95190 2.38290 2.80090 3.20690 3.60390 3.99190 4.37190
U1= 3.22500 2.89600 2.69600 2.56200 2.46300 2.38300 2.31600 2.25700 2.20400 2.15700 2.11400
U2= 2.39900 1.40800 0.89540 0.63500 0.49390 0.40930 0.35290 0.31180 0.27970 0.25340 0.23120

RUN 17A SUBRUN 2 ,S=0 TO .1713E+01
-U0= 0.00000 0.55230 1.05230 1.51930 1.96430 2.39330 2.81030 3.21630 3.61330 4.00230 4.38430
U1= 0.34450 3.04500 2.80700 2.65500 2.54800 2.46600 2.39900 0.23430 2.29400 2.25000 2.21100
U2= 0.30240 1.76500 1.08400 0.73020 0.53910 0.42710 0.35550 0.30590 0.26930 0.24100 0.21830

RUN 17B SUBRUN 1 ,S=0 TO .1682E+00
-U0= 0.00000 0.53800 1.03300 1.50100 1.94900 2.38100 2.80100 -0.38550 3.61000 4.00200 4.38600
U1= 0.33760 3.05300 2.85200 2.71500 2.61400 2.53200 2.46400 0.24050 2.35300 2.30600 2.26400
U2= 0.24650 1.48200 0.96290 0.68890 0.53430 0.43890 0.37460 0.32830 0.29320 0.26560 0.24340

RUN 17B SUBRUN 2 ,S=0 TO .1833E+00
-U0= 0.00000 0.53580 1.02080 1.47280 1.89980 2.30880 2.70080 -0.27170 3.44780 3.80580 4.15480
U1= 0.31070 2.76400 2.54500 2.39300 2.27700 2.18300 2.10400 0.20370 1.97800 1.92600 1.87900
U2= 0.23610 1.46300 0.97800 0.71580 0.56300 0.46470 0.39570 0.34360 0.30240 0.26870 0.24030

RUN 17C SUBRUN 1 ,S=0 TO .1753E+00
-U0= 0.00000 0.54200 1.04800 1.53300 2.00400 2.46500 2.91800 3.36400 3.80300 4.23700 4.66500
U1= 3.24300 2.96800 2.81700 2.72300 2.65800 2.60600 2.56300 2.52400 2.48900 2.45600 2.42600
U2= 2.11900 1.13200 0.65670 0.43430 0.32560 0.26750 0.23290 0.20990 0.19290 0.17950 0.16830

RUN 17C SUBRUN 2 ,S=0 TO .1779E+01
-U0= 0.00000 0.54030 1.03030 1.48830 1.92230 2.33830 2.74030 3.13030 3.51030 3.88030 4.24330
U1= 3.23300 2.87500 2.65100 2.49900 2.38600 2.29700 2.22400 2.16100 2.10800 2.06100 2.02100
U2= 2.57800 1.55700 1.01300 0.72420 0.55830 0.45250 0.37850 0.32300 0.27970 0.24480 0.21620

RUN 17D SUBRUN 1 ,S=0 TO .1807E+01
-U0= 0.00000 0.54580 1.05180 1.53280 1.99880 2.45180 2.89480 3.32880 3.75380 4.16980 4.57880
U1= 3.19000 2.88700 2.72000 2.61600 2.54000 2.49700 2.42500 2.37500 2.32900 2.28400 2.24200
U2= 2.26600 1.20900 0.70540 0.47660 0.36990 0.31610 0.28560 0.26570 0.25090 0.23840 0.22710

RUN 17D SUBRUN 2 ,S=0 TO .1758E+01
-U0= 0.00000 0.52200 1.02400 1.51400 1.99300 2.46600 2.93100 3.39100 3.84400 4.29300 4.73600
U1= 3.05700 2.90300 2.81400 2.75400 2.70700 2.66700 2.63000 2.59700 2.56600 2.53600 2.50800
U2= 1.18100 0.64210 0.40340 0.29620 0.24410 0.21550 0.19700 0.18350 0.17240 0.16280 0.15410

RUN 17E SUBRUN 1 ,S=0 TO .2207E+01
-U0= 0.00000 0.53340 1.03590 1.52080 1.99330 2.45580 2.90880 3.35380 3.79180 4.22080 4.64380
U1= 2.52400 2.33200 2.23100 2.16700 2.11700 2.07400 2.03500 1.99800 1.96300 1.93000 1.89800
U2= 1.22000 0.60510 0.34940 0.24800 0.20570 0.18500 0.17220 0.16250 0.15410 0.14650 0.13950

RUN 17E SUBRUN 2 ,S=0 TO .1971E+01
-U0= 0.00000 0.53530 1.03720 1.51940 1.98820 2.44700 2.89600 3.33800 3.77300 4.20100 4.62300
U1= 2.84500 2.61600 2.49000 2.41000 2.35100 2.30300 2.26100 2.22300 2.18800 2.15700 2.12700
U2= 1.58200 0.83380 0.49190 0.33900 0.26600 0.22640 0.20120 0.18290 0.16810 0.15570 0.14480

RUN 18A SUBRUN ,S=0 TO .1815E+01
-U0= 0.00000 0.53460 1.01800 1.46830 1.89510 2.30400 2.69800 3.08100 3.45300 3.81600 4.17200
U1= 3.13500 2.78200 2.56000 2.40900 2.29800 2.21000 2.13800 2.07700 2.02500 1.97900 1.93900
U2= 2.46900 1.51200 0.98830 0.70390 0.53910 0.43480 0.36290 0.30990 0.26870 0.23560 0.20830

RUN 19A SUBRUN ,S=0 TO .2288E+01
-U0= 0.00000 0.52920 1.01860 1.48470 1.93500 2.37300 2.80100 3.21900 3.63000 4.03300 4.43000
U1= 2.43900 2.20800 2.08000 1.99900 1.93900 1.89100 1.84900 1.81100 1.77800 1.74700 1.71900
U2= 1.37500 0.72640 0.43030 0.29720 0.23220 0.19560 0.17170 0.15400 0.13990 0.12800 0.11780

Table A4 (continued)

RUN 20A SUBRUN 1 ,S=0 TO .2861E+01

-U0=	0.00000	0.54160	1.00830	1.43110	1.82440	2.19540	2.54840	2.88640	3.21140	3.52540	3.83040
U1=	2.08600	1.73700	1.54300	1.42100	1.33200	1.26300	1.20600	1.15800	1.11700	1.08200	1.05100
U2=	1.63700	0.88250	0.52010	0.35520	0.27020	0.21820	0.18190	0.15460	0.13310	0.11570	0.10140

RUN 20A SUBRUN 2 ,S=0 TO .3020E+01

-U0=	0.00000	0.54100	0.99920	1.40980	1.78870	2.14370	2.48070	2.80270	3.11170	3.40970	3.69970
U1=	1.99400	1.62700	1.42600	1.30100	1.21200	1.14400	1.08900	1.04300	1.00500	0.97190	0.94370
U2=	1.63200	0.87290	0.50660	0.34080	0.25490	0.20210	0.16540	0.13810	0.11700	0.10020	0.08670

RUN 20B SUBRUN 1 ,S=0 TO .3115E+01

-U0=	0.00000	0.52930	0.99630	1.42630	1.83040	2.21540	2.58440	2.94040	3.28640	3.62240	3.95040
U1=	1.84700	1.58000	1.43100	1.33500	1.26500	1.20900	1.16300	1.12500	1.09300	1.06600	1.04300
U2=	1.16600	0.61740	0.37060	0.25950	0.19930	0.16120	0.13300	0.11120	0.09388	0.07987	0.06845

RUN 20B SUBRUN 2 ,S=0 TO .3147E+01

-U0=	0.00000	0.52480	0.98730	1.41050	1.80500	2.17700	2.53200	2.87100	3.19700	3.51300	3.82000
U1=	1.80800	1.55100	1.39900	1.29500	1.21600	1.15200	1.10000	1.05600	1.02000	0.98860	0.96200
U2=	1.08100	0.60700	0.38900	0.28450	0.22390	0.18230	0.15100	0.12650	0.10700	0.09130	0.07853

RUN 20C SUBRUN 1 ,S=0 TO .3823E+01

-U0=	0.00000	0.51500	0.96270	1.36840	1.74460	2.09760	2.43260	2.75260	3.06160	3.36160	3.65360
U1=	1.47500	1.24300	1.10900	1.01800	0.95070	0.89800	0.85630	0.82260	0.79520	0.77270	0.75390
U2=	0.81620	0.44320	0.28060	0.20230	0.15500	0.12210	0.09767	0.07914	0.06483	0.05366	0.04486

RUN 20C SUBRUN 2 ,S=0 TO .3689E+01

-U0=	0.00000	0.52010	0.96970	1.37820	1.75900	2.11800	2.46100	2.79100	3.11000	3.41900	3.72200
U1=	1.55300	1.29500	1.15500	1.06500	1.00000	0.95030	0.91030	0.87790	0.85130	0.82910	0.81060
U2=	0.96470	0.49510	0.29270	0.20290	0.15340	0.12070	0.09715	0.07936	0.06560	0.05479	0.04617

RUN 20D SUBRUN 1 ,S=0 TO .3003E+01

-U0=	0.00000	0.52590	0.99620	1.42870	1.83170	2.21170	2.56970	2.91170	3.23870	3.55270	3.85670
U1=	1.88000	1.64400	1.49700	1.38800	1.30000	1.22700	1.16500	1.11200	1.06600	1.02800	0.99400
U2=	1.02800	0.59660	0.41030	0.32140	0.26620	0.22470	0.19080	0.16280	0.13950	0.12020	0.10420

RUN 20D SUBRUN 2 ,S=0 TO .3244E+01

-U0=	0.00000	0.53260	0.99060	1.40440	1.78720	2.14720	2.48720	2.81320	3.12520	3.42620	3.71920
U1=	1.81200	1.50400	1.33400	1.22400	1.14200	1.07700	1.02500	0.98110	0.94490	0.91430	0.88830
U2=	1.29300	0.67890	0.40800	0.28770	0.22210	0.17870	0.14670	0.12200	0.10240	0.08668	0.07394

RUN 20E SUBRUN 1 ,S=0 TO .3338E+01

-U0=	0.00000	0.52240	0.97730	1.38980	1.77140	2.12940	2.46840	2.78940	3.09840	3.39440	3.68140
U1=	1.71100	1.44600	1.29100	1.18600	1.10600	1.04100	0.98740	0.94270	0.90520	0.87360	0.00000
U2=	1.06200	0.58420	0.37040	0.27130	0.21470	0.17580	0.14610	0.12240	0.10300	0.08701	0.07371

RUN 20E SUBRUN 2 ,S=0 TO .3272E+01

-U0=	0.00000	0.52650	0.99380	1.42590	1.83360	2.22160	2.59460	2.95560	3.30660	3.64960	3.98560
U1=	1.74400	1.50100	1.36700	1.27900	1.21300	1.16200	1.12100	1.08700	1.06000	1.03700	1.01800
U2=	1.02100	0.52860	0.32110	0.22810	0.17570	0.14000	0.11330	0.09270	0.07652	0.06373	0.05354

RUN 21A SUBRUN 1 ,S=0 TO .2981E+01

-U0=	0.00000	0.51260	0.97510	1.40750	1.81930	2.21600	2.60000	2.97400	3.34000	3.69900	4.05200
U1=	1.84200	1.62000	1.49400	1.41200	1.35400	1.30800	1.27100	1.24100	1.21500	1.19300	1.17400
U2=	1.00200	0.54350	0.32980	0.22750	0.17150	0.13630	0.11170	0.09351	0.07952	0.06849	0.05962

RUN 21A SUBRUN 2 ,S=0 TO .3009E+01

-U0=	0.00000	0.51700	0.97480	1.39900	1.80150	2.18840	2.56340	2.92840	3.28540	3.63540	3.97940
U1=	1.86500	1.60000	1.45600	1.36900	1.30900	1.26400	1.22900	1.19900	1.17400	1.15300	1.13400
U2=	1.19700	0.62860	0.35910	0.23430	0.16990	0.13200	0.10700	0.08935	0.07619	0.06603	0.05797

RUN 21B SUBRUN 1 ,S=0 TO .3143E+01

-U0=	0.00000	0.51210	0.96230	1.37660	1.76740	2.14100	2.50100	2.85100	3.19100	3.52300	3.84800
U1=	1.77700	1.51100	1.36600	1.27700	1.21400	1.16600	1.12800	1.09600	1.06900	1.04600	1.02500
U2=	1.14700	0.60610	0.35120	0.23330	0.17200	0.13520	0.11050	0.09275	0.07933	0.06887	0.06050

RUN 21B SUBRUN 2 ,S=0 TO .2836E+01

-U0=	0.00000	0.51090	0.96980	1.39430	1.79330	2.17190	2.53290	2.87890	3.21290	3.53590	3.84790
U1=	1.92800	1.69500	1.55000	1.44800	1.36800	1.30200	1.24600	1.19800	1.15600	1.11900	1.08600
U2=	1.06700	0.62750	0.41850	0.31440	0.25400	0.01320	0.18260	0.15840	0.13850	0.12180	0.10760

RUN 21C SUBRUN 1 ,S=0 TO .2872E+01

-U0=	0.00000	0.51710	0.97700	1.40320	1.80550	2.19000	2.55900	2.91600	3.26200	3.59900	3.83700
U1=	1.94200	1.68300	1.53400	1.43800	1.36700	1.31100	1.26400	1.22300	1.18800	1.15700	1.13000
U2=	1.20600	0.66250	0.40370	0.28170	0.21730	0.17800	0.15090	0.13070	0.11470	0.10170	0.09080

RUN 21C SUBRUN 2 ,S=0 TO .2702E+01

-U0=	0.00000	0.51850	0.98280	1.41410	1.82280	2.21490	2.59290	2.95890	3.31690	3.66590	4.00790
U1=	2.06300	1.80000	1.64800	1.55000	1.47800	1.42300	1.37700	1.33900	1.30700	1.27800	1.25400
U2=	1.29400	0.71830	0.44020	0.30480	0.23090	0.18490	0.15310	0.12960	0.11150	0.09718	0.08549

RUN 21D SUBRUN 1 ,S=0 TO .2661E+01

-U0=	0.00000	0.51440	0.98160	1.41870	1.83430	2.23340	2.61840	2.99140	3.35440	3.70940	4.05640
U1=	2.05800	1.83000	1.69200	1.59900	1.52800	1.47100	1.42400	1.38400	1.34900	1.31800	1.29200
U2=	1.12700	0.64590	0.41510	0.30040	0.23560	0.19370	0.16350	0.14040	0.12190	0.10690	0.09430

RUN 21D SUBRUN 2 ,S=0 TO .2691E+01

-U0=	0.00000	0.52100	0.98500	1.41600	1.82400	2.21460	2.59200	2.95820	3.31470	3.66310	4.00410
U1=	2.08400	1.81000	1.65300	1.55300	1.48200	1.42600	1.38000	1.34200	1.30900	1.28000	1.25500
U2=	1.35800	0.74870	0.45120	0.30810	0.23200	0.18590	0.15470	0.13180	0.11410	0.10000	0.00850

Table A4 (continued)

RUN 21E SUBRUN 1 ,S=0 TO .2869E+01

-U0=	0.00000	0.51200	0.99550	1.46120	1.91370	2.35570	2.78870	3.21470	3.63270	4.04370	4.44970
U1=	1.85800	1.72600	1.65000	1.59900	1.55800	1.52500	1.49500	1.46900	1.44600	1.42400	1.40500
U2=	0.62900	0.33330	0.21040	0.15600	0.12740	0.10930	0.09624	0.08607	0.07779	0.07085	0.06490

RUN 21E SUBRUN 2 ,S=0 TO .2890E+01

-U0=	0.00000	0.52180	1.00120	1.45680	1.89620	2.32280	2.73980	3.14680	3.54680	3.93880	4.32480
U1=	1.91900	1.71700	1.61100	1.54600	1.49800	1.45900	1.42500	1.39600	1.37000	1.34700	1.32500
U2=	0.98200	0.48440	0.27610	0.18940	0.14810	0.12410	0.10770	0.09523	0.08516	0.07677	0.06963

RUN 22A SUBRUN ,S=0 TO .3086E+01

-U0=	0.00000	0.51140	0.98060	1.42380	1.84850	2.25750	2.65450	3.04150	3.41750	3.78650	4.14750
U1=	1.75700	1.57600	1.47300	1.40300	1.35000	1.30600	1.26800	1.23600	1.20700	1.18100	1.15800
U2=	0.79700	0.42620	0.26560	0.19350	0.15540	0.13110	0.11330	0.09933	0.08783	0.07816	0.06991

RUN 23A SUBRUN ,S=0 TO .3700E+01

-U0=	0.00000	0.51880	0.96980	1.38650	1.78170	2.16070	2.52670	2.88170	3.22770	3.56670	3.89870
U1=	1.55200	1.28800	1.16400	1.09400	1.04400	1.00500	0.97380	0.94730	0.92490	0.90590	0.88960
U2=	1.04200	0.46600	0.23930	0.15470	0.11650	0.09394	0.07797	0.06560	0.05563	0.04747	0.04072

RUN 24A SUBRUN ,S=0 TO .3605E+01

-U0=	0.00000	0.49500	0.94250	1.36190	1.76250	2.14940	2.52440	2.88940	3.24640	3.59640	3.94040
U1=	1.47000	1.29500	1.19700	1.13500	1.09000	1.05500	1.02600	1.00200	0.98040	0.96150	0.94460
U2=	0.65280	0.35270	0.20940	0.14260	0.10790	0.08718	0.07335	0.06333	0.05564	0.04950	0.04442

RUN 25A SUBRUN ,S=0 TO .4254E+01

-U0=	0.00000	0.50070	0.97700	1.43130	1.86560	2.28160	2.68160	3.06760	3.44160	3.80460	4.15960
U1=	1.21000	1.14700	1.09300	1.04300	0.99840	0.95840	0.92340	0.89280	0.86620	0.84310	0.82300
U2=	0.16920	0.13290	0.12180	0.11160	0.10000	0.08814	0.07699	0.06698	0.05820	0.05062	0.04411

RUN 26A SUBRUN ,S=0 TO .5099E+01

-U0=	0.00000	0.50100	0.97840	1.43360	1.86760	2.28460	2.68560	3.07360	3.45060	3.81860	4.17860
U1=	1.00800	0.95880	0.91380	0.87160	0.83380	0.80110	0.77330	0.74970	0.72970	0.71270	0.69830
U2=	0.10870	0.08994	0.08612	0.07882	0.06913	0.05926	0.05027	0.04252	0.03600	0.03060	0.02615

RUN 27A SUBRUN ,S=0 TO .5127E+01

-U0=	0.00000	0.49960	0.96990	1.41790	1.84790	2.25990	-2.05610	3.04290	3.41790	3.78290	4.13990
U1=	1.01500	0.94180	0.89460	0.85500	0.82000	0.78950	0.76310	0.74050	0.72110	0.70450	0.69010
U2=	0.20210	0.10590	0.08268	0.07259	0.06379	0.05534	0.04761	0.04082	0.03500	0.03008	0.02595

RUN 28A SUBRUN ,S=0 TO .5046E+01

-U0=	0.00000	0.49320	0.95180	1.38680	1.80240	2.20240	2.58840	2.96240	3.32540	3.67940	4.02640
U1=	1.02800	0.93720	0.88340	0.84220	0.80750	0.77780	0.75210	0.72990	0.71060	0.69380	0.67910
U2=	0.25540	0.12960	0.09064	0.07433	0.06349	0.05467	0.04723	0.04092	0.03560	0.03109	0.02727

Table A5: U-functions for atomising air R.T.D.

RUN 1B SUBRUN 1 ,S=0 TO .5350E+00

-U0=	0.00000	0.85400	1.61380	2.29420	2.91260	3.48400	4.01800	4.52300	5.00500	5.46800	5.91600
U1=	16.96000	15.04000	13.40000	12.09000	11.08000	10.30000	9.69400	9.21400	8.82500	8.50200	8.22900
U2=	37.46000	33.59000	27.59000	21.54000	16.52000	12.74000	10.01000	8.03900	6.59900	5.52500	4.70600

RUN 1B SUBRUN 2 ,S=0 TO .4463E+00

-U0=	0.00000	0.86500	1.64080	2.34070	2.97910	3.56900	4.12100	4.64300	5.14000	5.61800	6.08000
U1=	20.46000	18.34000	16.48000	14.94000	13.72000	12.76000	12.00000	11.40000	10.92000	10.51000	10.17000
U2=	49.22000	45.09000	38.21000	30.79000	24.22000	18.98000	15.01000	12.07000	9.88400	8.25100	7.01400

RUN 1C SUBRUN 1 ,S=0 TO .3524E+00

-U0=	0.00000	0.87600	1.66900	2.39050	3.05410	3.67160	4.25240	4.80400	5.33100	5.83900	6.32900
U1=	26.13000	23.63000	21.42000	19.59000	18.13000	16.96000	16.03000	15.28000	14.66000	14.15000	13.71000
U2=	73.91000	67.50000	57.33000	46.52000	37.00000	29.40000	23.61000	19.26000	15.97000	13.44000	11.47000

RUN 1C SUBRUN 2 ,S=0 TO .1594E+01

-U0=	0.00000	0.89340	1.59740	2.19340	2.74140	3.27040	3.79040	4.30840	4.82340	5.33640	5.84840
U1=	6.33000	4.92700	4.00000	3.54700	3.35800	3.28400	3.25300	3.23700	3.22700	3.21800	3.20800
U2=	9.44000	7.56800	4.12200	1.80400	0.72040	0.28710	0.12800	0.07477	0.06012	0.05850	0.06044

RUN 1D SUBRUN 1 ,S=0 TO .4050E+00

-U0=	0.00000	0.90700	1.72500	2.46350	3.13750	3.15960	4.34000	4.88800	5.40900	5.90300	6.38900
U1=	23.57000	21.26000	19.16000	17.39000	15.95000	14.81000	13.90000	13.17000	12.58000	12.08000	11.67000
U2=	58.39000	55.16000	47.99000	39.47000	31.54000	25.05000	20.04000	16.25000	13.37000	11.17000	9.44100

RUN 1D SUBRUN 2 ,S=0 TO .3754E+00

-U0=	0.00000	0.89800	1.70940	2.44600	3.12140	3.74800	4.33600	4.89300	5.42400	5.93400	6.42600
U1=	25.17000	22.72000	20.55000	18.75000	17.29000	16.14000	15.21000	14.47000	13.85000	13.34000	12.90000
U2=	67.35000	62.12000	53.09000	43.22000	34.44000	27.40000	22.04000	18.00000	14.94000	12.60000	10.76000

RUN 1E SUBRUN 1 ,S=0 TO .4538E+00

-U0=	0.00000	0.95100	1.80570	2.57050	3.25560	3.87300	4.43400	4.94800	5.42300	5.86700	6.28500
U1=	22.02000	19.89000	17.81000	15.93000	14.31000	12.94000	11.81000	10.88000	10.11000	9.47800	8.95500
U2=	46.50000	46.92000	43.91000	38.75000	32.92000	27.40000	22.60000	18.59000	15.31000	12.65000	10.48000

RUN 1E SUBRUN 2 ,S=0 TO .3556E+00

-U0=	0.00000	0.87600	1.66300	2.37580	3.02840	3.63470	4.20500	4.74700	5.26600	5.76700	6.25300
U1=	26.00000	23.34000	21.02000	19.13000	17.65000	16.50000	15.61000	14.90000	14.33000	13.86000	13.46000
U2=	77.90000	70.91000	59.34000	47.06000	36.48000	28.27000	22.22000	17.81000	14.59000	12.19000	10.37000

RUN 2B SUBRUN 1 ,S=0 TO .4022E+00

-U0=	0.00000	0.93600	1.77800	2.53670	3.22610	3.86110	4.45400	5.01400	5.54800	6.06100	6.55800
U1=	24.49000	22.07000	19.84000	17.93000	16.41000	15.22000	14.30000	13.58000	13.00000	12.54000	12.15000
U2=	60.34000	58.68000	51.86000	42.61000	33.51000	25.92000	20.13000	15.88000	12.79000	10.53000	8.85600

RUN 2B SUBRUN 2 ,S=0 TO .3553E+00

-U0=	0.00000	0.91500	1.74000	2.48800	3.17070	3.80160	4.39170	4.95000	5.48200	5.99300	6.48700
U1=	27.06000	24.46000	22.08000	20.07000	18.43000	17.14000	16.12000	15.31000	14.66000	14.13000	13.69000
U2=	74.42000	70.98000	62.23000	51.32000	40.88000	32.17000	25.41000	20.32000	16.51000	13.64000	11.45000

RUN 2C SUBRUN 1 ,S=0 TO .4438E+00

-U0=	0.00000	0.89000	1.68400	2.39370	3.03740	3.62970	4.18300	4.70600	5.20500	5.68400	6.14700
U1=	21.21000	18.92000	16.87000	15.19000	13.87000	12.87000	12.09000	11.49000	11.01000	10.61000	10.28000
U2=	52.60000	49.60000	42.32000	33.68000	25.88000	19.76000	15.28000	12.09000	9.80700	8.15900	6.94400

RUN 2C SUBRUN 2 ,S=0 TO .3837E+00

-U0=	0.00000	0.91900	1.74300	2.48300	3.15350	3.76790	4.33800	4.87200	5.37800	5.86000	6.32200
U1=	25.23000	22.68000	20.33000	18.32000	16.69000	15.39000	14.36000	13.53000	12.85000	12.29000	11.81000
U2=	67.17000	64.80000	57.19000	47.36000	37.92000	30.07000	24.01000	19.45000	16.02000	13.40000	11.37000

RUN 2D SUBRUN 1 ,S=0 TO .4071E+00

-U0=	0.00000	0.90700	1.72040	2.45150	3.11530	3.72600	4.29500	4.83100	5.34100	5.82900	6.29800
U1=	23.50000	21.10000	18.91000	17.07000	15.60000	14.45000	13.54000	12.82000	12.24000	11.75000	11.34000
U2=	59.75000	57.11000	49.73000	40.55000	31.96000	25.00000	19.74000	15.87000	13.01000	10.87000	9.22100

RUN 2D SUBRUN 2 ,S=0 TO .4078E+00

-U0=	0.00000	0.89600	1.69830	2.41970	3.07620	3.68300	4.25000	4.78800	5.30200	5.79600	6.27500
U1=	23.19000	20.78000	18.62000	16.83000	15.43000	14.35000	13.52000	12.87000	12.35000	11.93000	11.58000
U2=	60.40000	56.83000	48.61000	38.90000	30.09000	23.11000	17.93000	14.17000	11.44000	9.42400	7.91000

RUN 2E SUBRUN 1 ,S=0 TO .5486E+00

-U0=	0.00000	0.91100	1.70900	2.40770	3.02670	3.58500	4.09800	4.57700	5.03000	5.46200	5.87700
U1=	17.67000	15.55000	13.59000	11.95000	10.68000	9.72500	9.01200	8.47100	8.05000	7.71400	7.44200
U2=	38.28000	37.93000	33.20000	26.48000	20.04000	14.95000	11.25000	8.64400	6.80800	5.48600	4.51100

RUN 2E SUBRUN 2 ,S=0 TO .3535E+00

-U0=	0.00000	0.90100	1.71300	2.44900	3.12150	3.74400	4.32680	4.87800	5.40200	5.90500	6.38900
U1=	26.81000	24.19000	21.83000	19.85000	18.26000	17.00000	16.00000	15.19000	14.51000	13.94000	13.44000
U2=	75.93000	71.22000	61.52000	50.26000	39.96000	31.68000	25.44000	20.85000	17.49000	15.00000	13.13000

RUN 6B SUBRUN 1 ,S=0 TO .5663E+00

-U0=	0.00000	0.74800	1.41310	2.01560	2.57220	3.09400	3.58900	4.06100	4.51500	4.95200	5.37500
U1=	14.10000	12.41000	11.13000	10.20000	9.49700	8.95900	8.52800	8.16900	7.86100	7.59000	7.34700
U2=	33.64000	26.10000	19.26000	14.18000	10.72000	8.43300	6.89700	5.83600	5.07600	4.51500	4.08700

RUN 6B SUBRUN 2 ,S=0 TO .5701E+00

-U0=	0.00000	0.76300	1.43550	2.04070	2.59690	3.11710	3.61000	4.08200	4.53700	4.97800	5.40800
U1=	14.32000	12.52000	11.15000	10.14000	9.40900	8.86500	8.44900	8.12000	7.85400	7.63300	7.44700
U2=	35.03000	27.80000	20.60000	14.95000	10.98000	8.28200	6.44200	5.15600	4.23000	3.54400	3.02200

Table A5 (continued)

RUN 6C SUBRUN 1 ,S=0 TO .6317E+00

-U0=	0.00000	0.74400	1.39750	1.98230	2.51590	3.01100	3.47600	3.91800	4.34000	4.74700	5.14000
U1=	12.62000	11.00000	9.75000	8.81300	8.11500	7.58200	7.16500	6.83000	6.55400	6.32200	6.12500
U2=	28.27000	22.68000	17.13000	12.73000	9.58400	7.40300	5.88200	4.79200	3.98700	3.37300	2.89300

RUN 6C SUBRUN 2 ,S=0 TO .7270E+00

-U0=	0.00000	0.79000	1.47500	2.07830	2.62040	3.11750	3.58080	4.01800	4.43600	4.83800	5.22700
U1=	11.68000	10.09000	8.80700	7.83400	7.11600	6.58300	6.18100	5.87100	5.62700	5.43000	5.26900
U2=	23.56000	19.93000	15.44000	11.47000	8.45800	6.32000	4.82200	3.76300	2.99900	2.43700	2.01400

RUN 6D SUBRUN 1 ,S=0 TO .7329E+00

-U0=	0.00000	0.76500	1.42600	2.00880	2.53250	3.01250	3.45930	3.88000	4.27900	4.66100	5.02800
U1=	11.25000	9.67700	8.43300	7.50500	6.81900	6.30400	5.90400	5.58400	5.32100	5.09900	4.90900
U2=	23.34000	19.30000	14.68000	10.83000	8.04400	6.14000	4.84300	3.93800	3.28300	2.79100	2.40900

RUN 6D SUBRUN 2 ,S=0 TO .7900E+00

-U0=	0.00000	0.76700	1.42400	1.99690	2.50680	2.97060	3.39980	3.80300	4.18500	4.55000	4.90100
U1=	10.51000	8.96500	7.73200	6.81000	6.13300	5.63200	5.25200	4.95700	4.72200	4.53000	4.37300
U2=	21.09000	17.68000	13.54000	9.96300	7.32000	5.48100	4.21100	3.31700	2.67100	2.19000	1.82200

RUN 6E SUBRUN 1 ,S=0 TO .7027E+00

-U0=	0.00000	0.76700	1.43200	2.01870	2.54900	3.03760	3.49500	3.92800	4.34200	4.74100	5.12600
U1=	11.75000	10.13000	8.85300	7.90900	7.22000	6.71100	6.32400	6.02000	5.77300	5.56800	5.39400
U2=	25.14000	20.69000	15.64000	11.42000	8.36100	6.26700	4.84800	3.87000	3.17800	2.67500	2.29800

RUN 6E SUBRUN 2 ,S=0 TO .7308E+00

-U0=	0.00000	0.80200	1.49400	2.09870	2.63610	3.12260	3.57060	3.98900	4.38300	4.75800	5.11800
U1=	11.81000	10.18000	8.82300	7.76900	6.97300	6.37100	5.90800	5.54600	5.25600	5.01800	4.82100
U2=	23.63000	20.61000	16.44000	12.52000	9.42600	7.17200	5.56500	4.41400	3.57600	2.95200	2.47800

RUN 10B SUBRUN 1 ,S=0 TO .9104E+00

-U0=	0.00000	0.57800	1.11550	1.62490	2.11450	2.58890	3.05100	3.50200	3.94400	4.37800	4.80400
U1=	6.65800	6.09400	5.72900	5.47600	5.28800	5.13800	5.01300	4.90500	4.80900	4.72300	4.64600
U2=	7.73800	4.90200	3.27800	2.36200	1.82600	1.49300	1.27000	1.11100	0.99090	0.89540	0.81680

RUN 10B SUBRUN 2 ,S=0 TO .9562E+00

-U0=	0.00000	0.60100	1.15460	1.67590	2.17350	2.65300	3.11800	3.57200	4.01600	4.45200	4.88100
U1=	6.59400	6.00600	5.60300	5.31500	5.10100	4.93500	4.80200	4.69200	4.59900	4.51800	4.44700
U2=	7.44400	5.03200	3.51700	2.56800	1.95500	1.54300	1.25700	1.05200	0.90190	0.78870	0.70080

RUN 10C SUBRUN 1 ,S=0 TO .9613E+00

-U0=	0.00000	0.61800	1.17030	1.67650	2.14900	2.59610	3.02310	3.43400	3.83100	4.21800	4.59400
U1=	6.85200	6.04600	5.47900	5.07300	4.77100	4.53900	4.35300	4.20000	4.07300	3.96300	3.86800
U2=	9.92300	6.99100	4.94100	3.60400	2.73300	2.14800	1.74000	1.44500	1.22500	1.05600	0.92500

RUN 10C SUBRUN 2 ,S=0 TO .1083E+01

-U0=	0.00000	0.62800	1.17900	1.67290	2.12550	2.54620	2.94180	3.31700	3.67500	4.02000	4.35200
U1=	6.24000	5.40500	4.79800	4.35300	4.02000	3.76000	3.55300	3.38300	3.24000	3.11900	3.01500
U2=	8.94200	6.56000	4.75900	3.52500	2.69500	2.12800	1.72600	1.43100	1.20900	1.03600	0.89850

RUN 10D SUBRUN 1 ,S=0 TO .1131E+01

-U0=	0.00000	0.66000	1.22780	1.73190	2.19110	2.61790	3.02100	3.40400	3.77300	4.12900	4.47500
U1=	6.33600	5.38500	4.70800	4.23700	3.90300	3.65900	3.47200	3.32400	3.20300	3.10200	3.01500
U2=	9.72700	7.12000	4.96400	3.47100	2.50100	1.87300	1.45800	1.17400	0.97250	0.82450	0.71240

RUN 10D SUBRUN 2 ,S=0 TO .1075E+01

-U0=	0.00000	0.65800	1.22720	1.73390	2.19630	2.62590	3.03000	3.41500	3.78300	4.13600	4.47800
U1=	6.63100	5.66000	4.97100	4.48600	4.13600	3.87200	3.66400	3.49500	3.35300	3.23200	3.12600
U2=	1.05000	7.62300	5.33800	3.79300	2.80000	2.15900	1.73000	1.43200	1.21400	1.05000	0.92170

RUN 10E SUBRUN 1 ,S=0 TO .1147E+01

-U0=	0.00000	0.65800	1.22130	1.71800	2.16840	2.58540	2.97740	3.35000	3.70700	4.05000	4.38300
U1=	6.24800	5.27300	4.58200	4.10400	3.76500	3.51600	3.32500	3.17300	3.04800	2.94400	2.85500
U2=	9.84200	7.17600	4.97700	3.47100	2.50500	1.88500	1.47500	1.19300	0.98960	0.83770	0.72020

RUN 10E SUBRUN 2 ,S=0 TO .1190E+01

-U0=	0.00000	0.65100	1.20490	1.69310	2.13530	2.54440	2.92850	3.29300	3.64200	3.97700	4.30200
U1=	5.97600	5.01500	4.34600	3.88700	3.56300	3.32400	3.14000	2.99300	2.87300	2.77300	2.68800
U2=	9.43900	6.74900	4.61500	3.20300	2.31500	1.74900	1.37200	1.10900	0.91670	0.77120	0.65780

RUN 16B SUBRUN 1 ,S=0 TO .1428E+01

-U0=	0.00000	0.56470	1.07510	1.54800	1.99590	2.42300	2.83400	3.23100	3.61700	3.99400	4.36200
U1=	4.20300	3.74000	3.43100	3.21600	3.05500	2.93000	2.82800	2.74300	2.67000	2.60600	2.55000
U2=	3.98000	2.61100	1.77900	1.28500	9.82500	7.86100	6.50400	5.51600	4.76300	4.16800	3.68600

RUN 16B SUBRUN 2 ,S=0 TO .1372E+01

-U0=	0.00000	0.56810	1.08080	1.55440	1.99920	2.42100	2.82500	3.21400	3.58900	3.95300	4.30600
U1=	4.40400	3.91500	3.57900	3.33800	3.15400	3.00700	2.88500	2.78100	2.69000	2.61100	2.54000
U2=	4.31500	2.92000	2.04700	1.51700	1.18700	0.96960	0.81710	0.70410	0.61650	0.54620	0.48810

RUN 16C SUBRUN 1 ,S=0 TO .1514E+01

-U0=	0.00000	0.54820	1.05590	1.53750	2.00060	2.45000	2.88700	3.31400	3.73300	4.14500	4.54900
U1=	3.80100	3.46500	3.25600	3.11400	3.00800	2.92400	2.85400	2.79400	2.74100	2.69400	2.65100
U2=	2.83600	1.71400	1.11300	0.79400	0.61410	0.50340	0.42840	0.37300	0.32940	0.29350	0.26320

RUN 16C SUBRUN 2 ,S=0 TO .1459E+01

-U0=	0.00000	0.55120	1.05960	1.54020	2.00090	2.44600	2.87800	3.29900	3.71000	4.11200	4.50600
U1=	3.97200	3.60600	3.37600	3.21900	3.09900	3.00300	2.92100	2.84800	2.78400	2.72500	2.67200
U2=	3.19100	1.94300	1.27600	0.92320	0.72650	0.60640	0.52560	0.46640	0.42020	0.38260	0.35100

Table A5 (continued)

RUN 16D SUBRUN 1 ,S=0 TO .1621E+01

-U0=	0.00000	0.54720	1.06090	1.55480	2.03490	2.50490	2.96590	3.41790	3.86290	4.30190	4.73390
U1=	3.52600	3.25300	3.09900	3.00100	2.92900	2.86900	2.81700	2.76900	2.72500	2.68400	2.64500
U2=	2.26200	1.22600	0.73460	0.50780	0.39910	0.34170	0.30690	0.28230	0.26260	0.24560	0.23020

RUN 16D SUBRUN 2 ,S=0 TO .1796E+01

-U0=	0.00000	0.55500	1.07020	1.56300	2.04120	2.50800	2.96600	3.41500	3.85700	4.29100	4.71800
U1=	3.25500	2.95600	2.79700	2.70000	2.63000	2.57400	2.52400	2.48000	2.43800	2.40000	2.36400
U2=	2.28100	1.17900	0.66760	0.44360	0.34230	0.29130	0.26100	0.23950	0.22200	0.20670	0.19270

RUN 16E SUBRUN 1 ,S=0 TO .1892E+01

-U0=	0.00000	0.54690	1.05380	1.53630	2.00150	2.45300	2.89200	3.32000	3.73800	4.14700	4.54800
U1=	3.04500	2.76400	2.60500	2.50000	2.41900	2.35100	2.29000	2.23500	2.18400	2.13800	2.09600
U2=	1.99700	1.08100	0.66040	0.47510	0.38750	0.33870	0.30540	0.27870	0.25540	0.23430	0.21490

RUN 16E SUBRUN 2 ,S=0 TO .1785E+01

-U0=	0.00000	0.54020	1.04760	1.53480	2.00790	2.47000	2.92100	3.36500	3.80000	4.22800	4.64800
U1=	3.16400	2.91900	2.77900	2.68700	2.61700	2.55900	2.50700	2.46000	2.41700	2.37700	2.34000
U2=	1.84400	1.00600	0.61600	0.43840	0.35260	0.30540	0.27480	0.25170	0.23230	0.21520	0.19980

RUN 20B SUBRUN 1 ,S=0 TO .3455E+01

-U0=	0.00000	0.52980	1.00320	1.44220	1.85580	2.24780	2.62280	2.98180	3.32880	3.66480	3.99080
U1=	1.65600	1.43600	1.31400	1.23000	1.16400	1.10800	1.06100	1.02100	0.98670	0.95680	0.93080
U2=	0.89530	0.44930	0.28110	0.21270	0.17460	0.14720	0.12550	0.10770	0.09292	0.08057	0.07022

RUN 20B SUBRUN 2 ,S=0 TO .3522E+01

-U0=	0.00000	0.52970	0.99890	1.43350	1.84350	2.23550	2.61150	2.97450	3.32550	3.66750	4.00150
U1=	1.63700	1.40000	1.27600	1.19700	1.13700	1.08800	1.04800	1.01300	0.98400	0.95850	0.93620
U2=	0.95370	0.46320	0.26990	0.19190	0.15150	0.12510	0.10540	0.09007	0.07773	0.06765	0.05931

RUN 20C SUBRUN 1 ,S=0 TO .3213E+01

-U0=	0.00000	0.52990	0.99820	1.42960	1.83490	2.21790	2.58290	2.93190	3.26590	3.58790	3.89890
U1=	1.79200	1.53400	1.39200	1.29800	1.22400	1.16300	1.11000	1.06300	1.02100	0.98320	0.94900
U2=	1.10700	0.57010	0.34710	0.25430	0.20700	0.17680	0.15480	0.13750	0.12350	0.11170	0.10160

RUN 20C SUBRUN 2 ,S=0 TO .3459E+01

-U0=	0.00000	0.52970	0.99080	1.41010	1.79850	2.16250	2.50550	2.83150	3.14250	3.44050	3.72750
U1=	1.68000	1.41300	1.26500	1.16400	1.08500	1.02000	0.96540	0.91890	0.87920	0.84530	0.81610
U2=	1.06600	0.54710	0.33950	0.25330	0.20580	0.17230	0.14570	0.12400	0.10590	0.09082	0.07827

RUN 20D SUBRUN 1 ,S=0 TO .3546E+01

-U0=	0.00000	0.52570	0.98940	1.41570	1.81540	2.19240	2.55240	2.89740	3.22940	3.55140	3.86240
U1=	1.61400	1.37800	1.24800	1.16100	1.09400	1.03900	0.99290	0.95390	0.92050	0.89150	0.86630
U2=	0.92650	0.47010	0.28900	0.21250	0.17020	0.14110	0.11910	0.10160	0.08755	0.07602	0.06649

RUN 20D SUBRUN 2 ,S=0 TO .3181E+01

-U0=	0.00000	0.52980	1.00640	1.45080	1.87130	2.27330	2.65830	3.02930	3.38930	3.73830	4.07830
U1=	1.79000	1.56600	1.44100	1.35600	1.29000	1.23500	1.18800	1.14800	1.11300	1.08200	1.05400
U2=	0.97380	0.50110	0.31100	0.23120	0.18830	0.15900	0.13650	0.11840	0.10360	0.09137	0.08126

RUN 20E SUBRUN 1 ,S=0 TO .3181E+01

-U0=	0.00000	0.52980	1.00640	1.45080	1.87130	2.27330	2.65830	3.02930	3.38930	3.73830	4.07830
U1=	1.79000	1.56600	1.44100	1.35600	1.29000	1.23500	1.18800	1.14800	1.11300	1.08200	1.05400
U2=	0.97380	0.50110	0.31100	0.23120	0.18830	0.15900	0.13650	0.11840	0.10360	0.09137	0.08126

RUN 20E SUBRUN 2 ,S=0 TO .3261E+01

-U0=	0.00000	5.29100	10.03300	14.44900	6.73000	7.13000	7.51500	7.88700	8.24900	8.60100	8.94500
U1=	1.75000	1.52200	1.39700	1.31500	1.25300	1.20200	1.16000	1.12400	1.09300	1.06700	1.04400
U2=	0.97090	0.49310	0.29810	0.21560	0.17140	0.14170	0.11920	0.10130	0.08686	0.07499	0.06517

Table A6: Moment analysis of drying air R.T.D.

Run	$\bar{t}$ /s	σ^2	Pe
5a	12.6	.051	38.9
b	11.0	.082	24.4
c	11.0	.082	24.4
d	11.5	.076	26.3
e	10.8	.086	23.4
9a	8.5	.168	11.9
b	8.6	.133	15.0
c	8.7	.175	11.4
d	8.7	.200	10.0
e	8.5	.225	8.9
14a	3.3	.080	25.0
b	4.1	.025	77.0
c	3.9	.024	89.0
d	3.8	.020	98.0
e	3.7	.040	49.8
17a	3.1	.174	11.5
b	3.0	.155	12.9
c	3.0	.144	13.9
d	2.9	.179	11.2
e	2.6	.114	17.5
21a	1.89	.40	5.05
b	1.89	.40	5.00
c	2.02	.37	5.35
d	2.05	.30	6.65
e	1.85	.148	13.5
24a	1.49	.36	5.53

Note: (1) Notation follows chapter 3.

(2) See chapter 3 for operating conditions.

(3) Pe calculated from $Pe = 2/\sigma^2$.

Table A7: Transfer function analysis (A.D.P.F. and T.S.P.F. models) of drying air R.T.D.

Run No.	A.D.P.F.		T.S.P.F.			Run No.	A.D.P.F.		T.S.P.F.		
	τ/s	Pe	n	T_t/s	T_p/s		τ/s	Pe	n	T_t/s	T_p/s
1a	34.3	13.9	2.07	26.3	11.8	12a	5.43	14.3	2.06	2.86	2.44
b	29.7	12.4	3.52	24.3	7.0						
c	29.8	12.7	3.12	24.5	7.8	13a	4.92	11.0	1.79	2.87	2.01
d	25.0	9.6	1.73	28.1	7.6						
e	24.6	10.4	2.28	21.3	6.1	14a	3.99	13.6	1.44	1.82	2.07
						b	4.52	23.6	2.36	1.64	2.67
2a	34.3	13.9	2.07	26.3	11.8	c	4.22	30.5	4.02	1.72	2.26
b	27.6	11.3	2.44	24.4	7.8	d	4.11	28.4	5.50	1.98	3.94
c	28.9	12.2	2.90	25.0	7.7	e	4.23	19.2	2.47	1.46	3.93
d	28.5	11.4	4.98	24.9	3.7						
e	26.2	11.2	2.62	22.4	7.1	15a	3.84	13.7	1.60	1.87	1.90
3a	28.5	15.5	1.51	18.3	13.5	16a	3.67	15.2	1.76	1.69	1.86
						b	3.54	11.5	1.48	1.87	1.62
4a	17.3	12.0	1.82	11.1	6.84	c	3.58	19.7	2.62	1.71	1.77
						d	3.65	28.7	7.09	2.08	1.44
5a	16.3	13.5	1.59	10.4	7.21	e	3.54	21.8	3.71	1.84	1.59
b	14.7	9.3	1.61	12.8	4.87						
c	14.9	8.7	2.29	11.7	3.92	17a	3.17	14.0	2.17	1.54	1.48
d	15.9	9.1	2.32	12.3	4.30	b	3.11	13.5	2.35	1.67	1.34
e	14.9	8.3	1.82	12.6	4.30	c	3.09	17.8	2.05	1.37	1.62
						d	2.99	29.3	5.30	1.48	1.39
6a	15.2	15.4	2.80	9.7	5.8	e	2.56	25.9	6.02	1.33	1.13
b	15.3	10.0	2.60	11.9	4.1						
c	14.6	9.8	3.19	11.0	3.4	18a	3.01	11.7	1.75	1.59	1.34
d	14.1	8.4	3.19	11.8	2.6						
e	13.6	8.3	1.79	11.5	4.1	19a	2.31	18.9	2.78	1.05	1.16
7a	12.0	13.9	2.29	6.99	4.88	20a	1.92	6.9	1.86	1.24	0.58
						b	1.74	9.0	1.61	1.08	0.66
8a	9.4	13.5	2.27	5.54	3.79	c	1.44	7.4	1.16	0.97	0.55
						d	1.78	8.0	2.08	1.27	0.51
9a	9.0	10.6	1.72	5.84	3.47	e	1.65	8.7	1.49	1.07	0.62
b	9.2	16.2	2.77	5.17	3.85						
c	9.2	10.1	1.70	5.94	3.46	21a	1.73	14.8	1.11	0.80	0.90
d	9.2	8.4	1.92	6.58	2.84	b	1.76	9.4	1.98	1.06	0.65
e	8.8	7.9	1.45	6.31	3.03	c	1.89	10.4	1.84	1.03	0.80
						d	1.96	11.5	1.70	1.03	0.88
10a	7.2	10.9	1.09	4.54	3.35	e	1.80	20.9	2.27	0.76	0.98
b	7.3	17.1	2.29	3.78	3.42						
c	7.6	10.8	1.79	4.60	2.98	22a	1.67	14.8	2.29	0.87	0.76
d	7.0	6.2	1.31	5.67	2.10	23a	1.40	9.8	1.29	0.70	0.66
e	7.1	6.5	1.42	5.45	2.16	24a	1.38	12.4	1.61	0.64	0.68
						25a	1.22	17.5	2.70	0.80	0.47
11a	7.1	14.1	1.79	2.87	2.01	26a	1.02	17.2	1.73	0.61	0.48
						27a	.995	17.3	1.98	0.58	0.46
						28a	.993	15.4	2.19	0.58	0.43

Note: Notation follows chapter 3.

Table A8: Transfer-function analysis (A.D.P.F. and T.S.P.F. models) of atomising air R.T.D.

Run No.	A.D.P.F.		T.S.P.F.		
	τ/s	Pe	n	T_t	T_p
1b	19.7	10.1	2.22	17.1	5.6
c	27.1	12.4	2.58	21.6	8.3
d	25.6	11.8	2.74	21.5	7.0
e	27.1	11.4	2.09	22.3	8.8
2b	27.4	11.4	2.22	25.6	8.2
c	24.9	10.1	2.45	22.8	6.3
d	24.8	10.5	2.22	22.6	7.1
e	28.2	11.8	2.97	22.9	7.3
6b	14.4	10.0	1.52	10.6	5.3
c	12.8	7.7	1.75	11.2	3.6
d	11.8	6.3	1.93	10.1	2.6
e	12.8	6.7	1.85	11.2	3.0
10b	6.4	18.1	2.20	2.91	3.43
c	6.5	8.9	1.90	4.40	2.14
d	6.5	6.9	2.83	4.64	1.91
e	6.3	6.1	1.54	4.56	1.75
16b	4.19	11.3	2.17	2.48	1.60
c	3.73	17.7	2.38	1.79	1.83
d	3.22	24.9	4.07	1.48	1.60
e	2.97	22.3	4.44	1.59	1.26
20b	1.55	10.6	2.15	0.97	0.56
c	1.65	8.5	3.35	1.25	0.34
d	1.61	10.4	2.37	1.04	0.54
e	1.57	10.4	1.67	0.95	0.63

Note: (1) Run 1 done with nozzle no. 1; other runs done with nozzle no. 2.

(2) Notation follows chapter 3.

(3) Values given are average of 2 readings.

Table A9: Transfer-function analysis (D.B.M. and B.C.P.F. models) of drying air R.T.D.

Run	D.B.M. + Plug flow				Backflow cell + P.F.			
	1/k	T_o/s	T_p/s	τ/s	n	b	T_t/s	T_p/s
1a	NA	-	-	-				
b	NA	-	-	-				
c	NA	-	-	-				
d	NA	-	-	-				
e	NA	-	-	-				
2a	NA	-	-	-				
b	NA	-	-	-				
c	NA	-	-	-				
d	NA	-	-	-				
e	NA	-	-	-				
6a	NA	-	-	-	3.69	+.24	9.8	5.5
b	NA	-	-	-	2.44	-.12	11.0	4.2
c	NA	-	-	-	3.28	-.01	11.0	3.3
d	NA	-	-	-	3.18	-.03	11.3	2.6
e	NA	-	-	-	1.61	-.22	9.9	4.1
10a	9.6	13.4	3.20	9.13	1.10	-.07	4.09	3.33
b	2.05	3.07	2.86	7.11	2.74	+.16	4.00	3.35
c	3.53	7.05	2.63	8.21	2.40	+.25	5.10	2.81
d	NA	-	-	-	1.22	-.20	4.65	2.12
e	NA	-	-	-	1.52	-.05	5.00	2.11
16a	2.38	1.53	1.57	3.38				
b	4.01	1.69	1.43	3.47				
c	1.63	0.96	1.39	3.36				
d	1.10	0.30	0.22	3.40				
e	1.33	0.67	1.00	3.32				
20a	3.17	1.56	0.47	1.83	2.20	+.26	1.38	0.56
b	3.66	1.62	0.56	1.82	1.57	-.04	1.11	0.67
c	7.38	2.61	0.47	1.79	1.00	-.16	0.86	0.57
d	2.85	1.48	0.38	1.87	1.80	-.07	1.23	0.54
e	3.88	1.62	0.51	1.75	1.21	-.14	0.99	0.65

Notes: (1) NA: not applicable.
(2) T_t is total tank time.
(3) Notation follows chapter 3.

Table A10: Output concentration curves for spray R.T.D.

SPRAY R.T.D. DATA FOR RUN A1 AT TIME INTERVALS DT= 0.513 (STARTING AT T=DT)

0	0	0	0	0	0	0	0	2	15	23	34	69	133	155	196	240	469	479	561
424	428	473	540	622	778	727	690	705	710	786	999	770	750	694	686	672	610	756	962
851	695	675	601	597	603	580	654	741	593	416	460	447	406	420	396	352	329	313	282
230	213	261	232	163	141	126	147	148	113	109	91	81	90	89	110	92	63	72	79
82	76	77	74	70	74	77	57	44											

SPRAY R.T.D. DATA FOR RUN A2 AT TIME INTERVALS DT= 0.513 (STARTING AT T=DT)

0	0	0	1	1	1	1	14	67	118	187	257	348	348	403	464	615	648	801	781
839	995	999	939	586	672	419	403	445	466	501	472	445	343	319	299	368	383	397	330
277	232	228	203	179	150	152	134	194	130	136	130	127	123	132	138	159	136	114	85
87	87																		

SPRAY R.T.D. DATA FOR RUN A3 AT TIME INTERVALS DT= 0.513 (STARTING AT T=DT)

0	0	96	669	378	921	989	921	775	756	436	756	999	756	552	378	455	203	300	271
339	213	271	213	223	184	223	106	145	106	145	106	213	145	87	116	77	193	87	67
96	58	58	38	58	58	29	29	29	27	12	11	18	2	0	9	0	0	1	4

SPRAY R.T.D. DATA FOR RUN B3 AT TIME INTERVALS DT= 0.513 (STARTING AT T=DT)

0	0	0	23	202	466	782	999	956	909	937	777	782	631	395	433	419	343	230	193
127	127	136	113	84	56	61	61	51	42	47	37	32	18	23	18				

SPRAY R.T.D. DATA FOR RUN C3 AT TIME INTERVALS DT= 0.513 (STARTING AT T=DT)

0	0	73	91	174	568	989	476	999	714	531	476	687	641	458	274	284	174	229	201
91	82	119	73	128	64	54	36	64	45	27	27	27	36	36					

SPRAY R.T.D. DATA FOR RUN D3 AT TIME INTERVALS DT= 0.355 (STARTING AT T=DT)

0	0	0	0	739	819	739	999	559	479	153	253	139	53	39	19	6	19	6	13
6	0	6	0																	

SPRAY R.T.D. DATA FOR RUN E3 AT TIME INTERVALS DT= 0.209 (STARTING AT T=DT)

68	342	684	985	999	821	615	478	369	307	273	246	218	205	239	205	164	136	109	88
68	47	34	20	13																

Table A11: U-functions for spray R.T.D.

RUN A1 ,S=0 TO .4170E+00

-U0=	0.00000	0.78100	1.49700	2.15200	2.75600	3.31700	3.84100	4.33400	4.80300	5.24900	5.67700
U1=	19.69000	17.97000	16.41000	15.07000	13.93000	12.98000	12.18000	11.52000	10.96000	10.48000	10.06000
U2=	42.92000	39.58000	34.85000	29.74000	2.49400	2.07900	1.73700	14.61000	12.42000	10.67000	9.26800

RUN A2 ,S=0 TO .4995E+00

-U0=	0.00000	0.67700	1.29200	1.85600	2.38100	2.87300	3.33800	3.78100	4.20400	4.60900	4.99800
U1=	14.29000	12.88000	11.76000	10.87000	10.16000	9.57000	9.07800	8.65400	8.28200	7.95000	7.65000
U2=	30.90000	25.17000	19.99000	15.89000	12.86000	10.68000	9.10000	7.92700	7.02400	6.30400	5.70900

RUN A3 ,S=0 TO .1007E+01

-U0=	0.00000	0.61100	1.14300	1.61400	2.03900	2.42800	2.78900	3.12800	3.44700	3.75200	4.04300
U1=	6.53000	5.64400	4.95200	4.42600	4.02400	3.71200	3.46400	3.26200	3.09400	2.95200	2.83000
U2=	9.76900	7.80400	5.97600	4.54000	3.49400	2.74700	2.21100	1.81900	1.52600	1.30200	1.12800

RUN B3 ,S=0 TO .8972E+00

-U0=	0.00000	0.54700	1.05000	1.51900	1.96000	2.37900	2.77900	3.16300	3.53300	3.89100	4.23900
U1=	6.38000	5.83200	5.40200	5.06100	4.78600	4.55800	4.36500	4.20000	4.05600	3.92900	3.81600
U2=	6.90200	5.39100	4.24000	3.39700	2.78100	2.32600	1.98200	1.74100	1.50200	1.33100	1.18900

RUN C3 ,S=0 TO .9798E+00

-U0=	0.00000	0.56700	1.08300	1.55700	1.99800	2.41200	2.80300	3.17400	3.52800	3.86600	4.18900
U1=	6.10200	5.50600	5.03400	4.65800	4.35300	4.10000	3.88400	3.69500	3.52700	3.37500	3.23400
U2=	6.80100	5.40100	4.27600	3.43400	2.82100	2.37600	2.05100	1.81000	1.62900	1.49000	1.38000

RUN D3 ,S=0 TO .1787E+01

-U0=	0.00000	0.49200	0.96200	1.41300	1.84700	2.26900	2.67800	3.07700	3.46700	3.84900	4.22500
U1=	2.82500	2.68600	2.57100	2.47500	2.39300	2.32200	2.26000	2.20700	2.16000	2.11800	2.08200
U2=	0.86150	0.70350	0.58630	0.49670	0.42600	0.36860	0.32100	0.28090	0.24660	0.21710	0.19160

RUN E3 ,S=0 TO .2930E+01

-U0=	0.00000	0.44900	0.83500	1.17300	1.47900	1.75900	2.01900	2.26400	2.49500	2.71400	2.92300
U1=	1.67200	1.41300	1.22600	1.09300	0.99530	0.92040	0.86050	0.81070	0.76780	0.72990	0.69590
U2=	1.02400	0.74980	0.53440	0.38590	0.28900	0.22630	0.18510	0.15700	0.13700	0.12210	0.11070

Table A12: Moment analysis and transfer-function analysis (A.D.P.F. and T.S.P.F. models) of spray R.T.D.

Run	Moment Analysis			Transfer-function analysis				
				A.D.P.F.		T.S.P.F.		
	$\bar{t}$/s	σ^2	Pe	τ/s	Pe	n	T_t/s	T_p/s
A1	12.0	0.037	54.8	20.5	11.8	3.76	17.4	4.1
A2	10.0	0.044	45.4	14.4	11.3	4.42	11.2	2.7
A3	4.96	0.125	16.0	6.92	5.7	2.15	5.64	1.28
B3	5.57	0.091	21.9	6.36	11.9	2.82	4.32	2.00
C3	5.10	0.095	21.0	6.16	9.7	4.76	5.12	7.52
D3	2.80	0.096	20.9	2.81	21.2	2.14	1.42	1.43
E3	1.71	0.387	5.17	1.74	3.96	2.15	1.32	0.23

APPENDIX B

MISCELLANEOUS EXPERIMENTS

Contents

APPENDIX B

MISCELLANEOUS EXPERIMENTS

B.I DROP SIZES FROM PNEUMATIC ATOMISERS

B.I.1 Aims of experiments

Experiments were carried out in order to

(1) Measure the mean drop size of a pneumatic atomiser at varying air and liquid rates, and check various predictive equations.

(2) Find the shape of the drop-size spectrum.

(3) Find the influence of the presence of an undissolved solid (zinc oxide) on the drop sizes.

(4) Find the influence of the drying-air flow on the drop sizes.

B.I.2 Theory

Equations for predicting either the Sauter diameter D_{32} or the mass median diameter D_m of a spray from a pneumatic nozzle have been proposed by many workers and reviewed in references 2, 4, 6 and 7. It appears from all these works that the variables governing the droplet sizes are: the viscosity, density and surface tension of each phase, the velocity or flow rate of each phase, the orifice diameters and configurations (i.e. internal or external mixing) of the nozzle.

The most commonly used drop-size distribution functions have been reviewed by Mugele and Evans (5). They are: the root-normal distribution, the log-normal distribution, the Nukiyama-Tasanawa distribution, and the Rosin-Rammler distribution. These and most other distribution equations proposed so far can be considered as particular cases of the following two groups:

(1) Normal distributions, with the normally distributed variable being $\sqrt{D}$, ln D or $\ln[aD/(D_{max} - D)]$ (5).

(2) Generalised Nukiyama-Tasanawa equations

$$\frac{dn}{dD} = aD^b \exp(-cD^d) \qquad \text{(B.1)}$$

where n is the number of droplets with size below D. If b = 2, the

standard Nukiyama-Tasanawa equation is obtained. If b = 0 and d = 1, one gets the log-number distribution. If b = d - 4, the Rosin-Rammler equation is obtained. Other authors have proposed b = d - 1 (3,10) and b = 1, d = 2 (Khrgian and Mazin, as quoted in 1).

B.I.3 Experimental details

The technique used for measuring drop sizes is to collect the droplets into a rectangular perspex cell (as described in chapter 4) with a 1 mm layer of Shell Carnea-69 oil, and to photograph them under a microscope. More details about the photographic technique can be found in chapter 4 and in references 9 and 11.

Nozzle No. 1 (table 1, chapter 1) was used. The nozzle was installed at the top of the spray drying chamber and the collecting cell placed 500 mm below it, about 20 mm below the point where the jet breaks up.

Eight runs were made with pure water as feed, at liquid rates ranging from 0.3 to 0.7 cm^3/s and atomising air rates ranging from 0.3-0.7 g/s. One run was made with a zinc-oxide slurry (30% solid by weight, viscosity = 0.005 N s/m^2) at a liquid rate of 0.5 cm^3/s and an atomising air rate of 1.3 g/s. One run was made with pure water at 0.5 cm^3/s of liquid and 1.3 g/s of atomising air, with a drying-air velocity of 1.9 m/s in the drying chamber.

B.I.4 Results and discussion

(1) Mean drop sizes: The measured Sauter mean diameters are shown in table 1. Also shown are the predicted values of D_{32} or D_m according to the equations of Nukiyama and Tasanawa, Wigg, Kim and Marshall, and Mugele. It can be seen that the Nukiyama-Tasanawa equation (8,7) for D_{32} gives the closest value, although it predicts that D_{32} is somewhat more sensitive to the flow rates than is the case.

(2) Size spectrum: Among the log-normal, root-normal, Nukiyama-Tasanawa and Rosin-Rammler distribution equations, the Nukiyama-Tasanawa equation fits the experimental spectrum best. The exponent d in equation 1 ranges from 0.35 to 0.60 for best fit (the best fit being measured by the correlation of a plot of $\ln\left[(dn/dD)/D^2 \right]$ vs D^d), but a value of $d \sim 0.5$ seems best for predicting the various mean diameters, although the other equations are also fairly good. Typical plots for various distribution equations are shown in figure 1, with the best fit value of d.

(3) Effect of undissolved solids:

The presence of fine (below 1 μm) zinc-oxide particles increases the viscosity of the feed from 0.001 to 0.005 N s/m^2 but does not seem to affect the mean drop size (D_{32} = 36 μm for pure water, = 37 μm for slurry), although the size distribution appears wider (d ≃ 0.5 for pure water, ≃ 0.3 for slurry). However, this result is somewhat inconclusive, due to the fact that the flow of slurry was not measured directly but was assumed to be the same as the flow of water under the same atomising conditions.

(4) Effect of external air flow:

When the external (drying) air velocity is increased from 0 to 1.9 m/s, the Sauter mean diameter is decreased from 36 to 31.5 μm. This is probably due to the turbulence in the external air flow breaking up the jet at an early stage, thus preventing recoalescence.

Table B.1

Measured and predicted mean diameters

of droplets from a pneumatic nozzle

Air rate /g s^{-1}	Liquid rate /cm^3 s^{-1}	D_{32} meas'd /μm	D_{32},N.T. /μm	D_m,Wigg /μm	D_m,K.M. /μm	D_{32},Mugele /μm
0.6	0.3	58	70	480	23	170
	0.47	66	92	-	-	-
1.05	0.47	-	38	240	12	115
	0.58	54	44	-	-	-
1.3	0.50	36	29	190	9.5	105
	0.65	45	32	-	-	-
1.75	0.50	35	21	124	8.3	90
	0.70	42	23	-	-	-

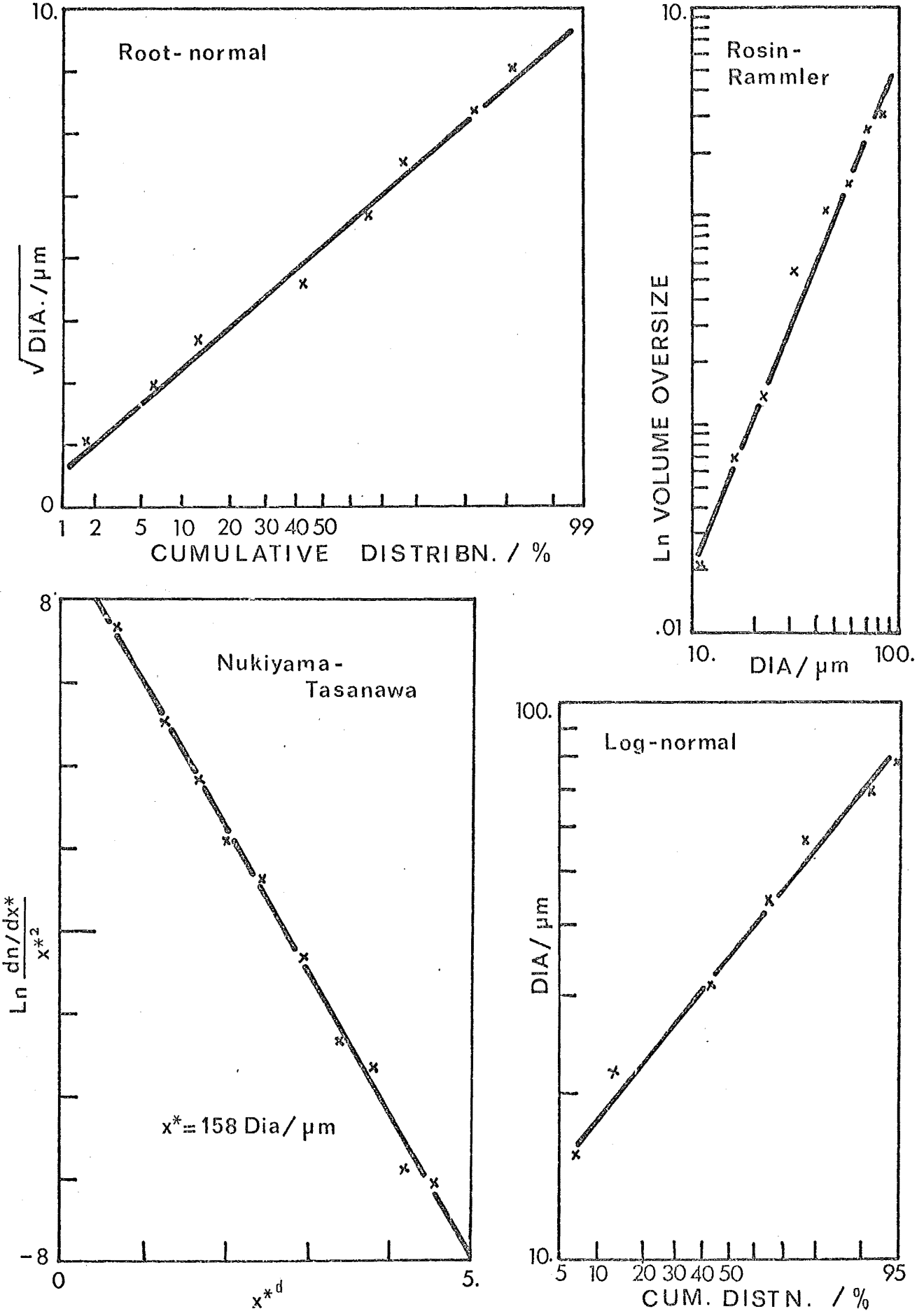

FIG. B1 : DROP SIZE ANALYSES

Notation for appendix B.I:

a,b,c,d	constants in equation 1
D	droplet diameter [m]
D_m	mass-median droplet diameter [m]
D_{max}	maximum droplet diameter [m]
D_{32}	surface-volume or Sauter mean droplet diameter [m]
n	number of droplets with size below D [-]

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(10) Shapiro A.H., Erickson A.J., Trans. A.S.M.E. 79 (1957) 775

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B.II ATOMISER AIR-FLOW AREA AND AIR FLOW RATE MEASUREMENTS

B.II.1 Aim of experiment

Knowledge of the air-flow rate and air-flow area of the nozzle is essential for the prediction of drop sizes and the calculation of jet zone velocity, temperature, concentration and evaporation profiles (chapter 6). The manufacturer's values were found to be unreliable, so a direct measurement of flow rates was necessary.

B.II.2 Theory

For the isentropic flow of an ideal gas through an orifice, the following equations apply (see, for example, reference 1):

$$\dot{m} = A\left\{\frac{2k}{k-1}\, p_1\rho_1 \left[\left(\frac{p_2}{p_1}\right)^{2/k} - \left(\frac{p_2}{p_1}\right)^{(k+1)/k} \right]\right\}^{\frac{1}{2}} \qquad \text{for} \quad \frac{p_2}{p_1} \geq \left(\frac{2}{k+1}\right)^{k/(k-1)} \tag{B.2}$$

$$\dot{m} = A\left\{k\, p_1\rho_1 \left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}\right\}^{\frac{1}{2}} \qquad \text{for} \quad \frac{p_2}{p_1} \leq \left(\frac{2}{k+1}\right)^{k/(k-1)} \tag{B.3}$$

where $\dot{m}$ is the gas mass flow rate, A the orifice area, k the specific heat ratio of the gas, p_1 and p_2 the upstream and downstream absolute pressures, and ρ_1 the upstream gas density. For a given downstream pressure p_2, since ρ_1 is proportional to p_1, equation 3 predicts that the mass flow rate $\dot{m}$ is directly proportional to the upstream absolute pressure p_1, provided that p_1 exceeds a certain critical value:

$$p_c = p_2 \left(\frac{k+1}{2}\right)^{k/(k-1)} \tag{B.4}$$

When the gas is air (k = 1.4) discharging into the atmosphere ($p_2 = 1.01 \times 10^5$ Pa), equations 3 and 4 reduce to

$$\dot{m} = 2.45 \times 10^{-3}\, Ap_1 \tag{B.5}$$

in S.I. units, provided

$$p_1 \geq p_c = 1.9 \times 10^5 \text{ Pa} \qquad (B.6)$$

This equation can be used to calculate A from a plot of $\dot{m}$ against p_1.

B.II.3 Experimental details

Each nozzle was allowed to discharge, under a variable and controlled pressure obtained with a regulating valve, into a 20 litre flask. The flow from the flask to the atmosphere was measured with a rotameter. The liquid inlet to the nozzle was plugged.

B.II.4 Results

For nozzles no. 1 and 2 (see table 1, chapter 1) $\dot{m}$ is plotted against p_1 in figure 2. The results agree well with the theory. From the slopes of the plots, the airflow areas of each nozzle can be calculated:

Nozzle 1: A = 1.4 mm^2 (manufacturer's value = 0.81 mm^2)

Nozzle 2: A = 2.3 mm^2 (manufacturer's value = 1.2 mm^2)

Notation for appendix B.II

A	discharge area	[m^2]
k	constant pressure/constant volume specific heat ratio of gas	[-]
$\dot{m}$	mass flow rate of gas	[kg/s]
p_1	upstream or atomising absolute pressure	[Pa]
p_2	downstream or atmospheric absolute pressure	[Pa]
p_c	critical pressure	[Pa]
ρ_1	gas density at pressure p_1	[kg/m^3]

Reference

(1) Bird R.B., Stewart W.E., Lightfoot E.N., "Transport Phenomena", J. Wiley & Sons, N.Y. (1960)

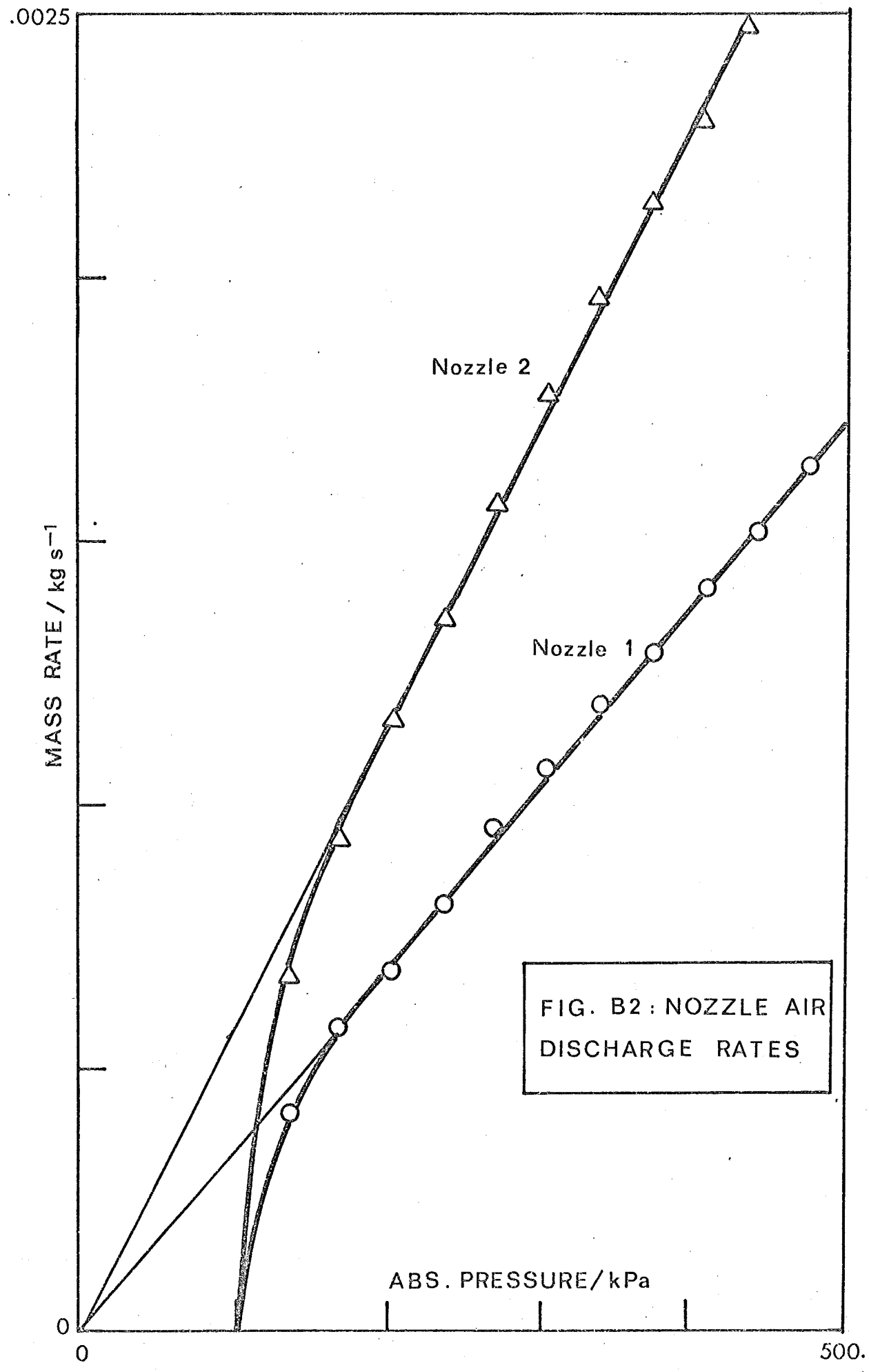


FIG. B2 : NOZZLE AIR DISCHARGE RATES

B.III SUSPENDED DROPLET DRYING TESTS WITH A ZINC OXIDE SLURRY

B.III.1 Aim of the experiment

(1) To investigate the process of shrinking and consolidation of drops of a zinc-oxide slurry.

(2) To find the relationship between the initial solid content and the final porosity for drops of the same material.

B.III.2 Background and theory

The mechanism of particle formation from evaporating droplets and its influence on the drying rate has been reviewed in chapter 5. Consider a simple process where a drop containing either dissolved or very finely dispersed solid (particle diameter << drop diameter) at first shrinks freely as the liquid evaporates, then suddenly stops shrinking when a solid structure forms. The weight-volume plot of such a drop would have the shape shown in figure 3.

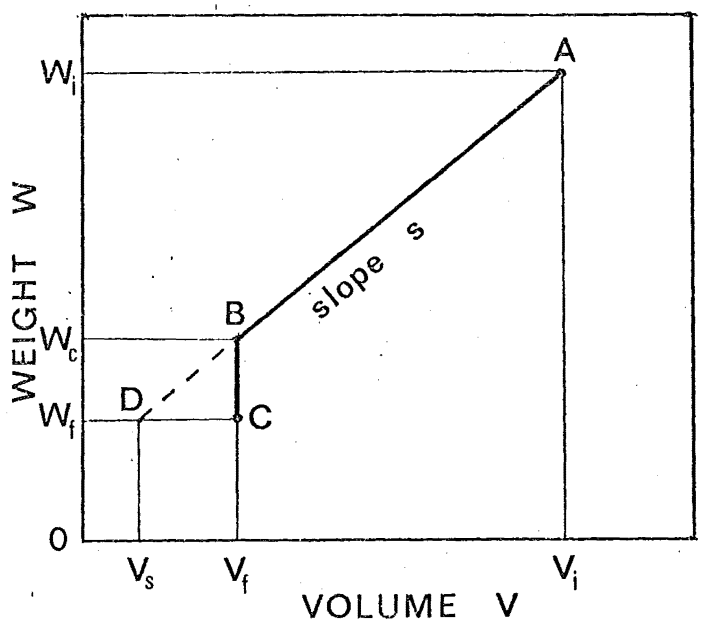


FIGURE B.3: TWO-PERIOD PARTICLE FORMATION

The point D (W_c, V_s) on the graph represents the state of a hypothetical dry particle formed from the original drop with no voidage, since the shrinkage continues until the particle is completely dry. Hence V_s is the actual volume of solid in the droplet or particle, and the void fraction ε_f of the dry particle is

$$\varepsilon_f = \frac{V_f - V_s}{V_f} \tag{B.7}$$

Similarly, it can be shown that the initial water volume fraction ε_i is

$$\varepsilon_i = \frac{V_i - V_s}{V_i} \tag{B.8}$$

From equations 7 and 8 it is seen that both the weight and the volume scales in figure 3 can be in arbitrary unit (for example, weights can be expressed in terms of the deflection of a support), and the point W = 0 is not required to be known.

By algebraic manipulation of equations 7 and 8, it can also be shown that

$$\varepsilon_f = \frac{W_c - W_f}{sV_f} \tag{B.9}$$

$$\varepsilon_i = \left\{ 1 + \frac{W_c - W_f}{W_i - W_f} \left(\frac{1}{\varepsilon_f} - 1 \right) \right\}^{-1} \tag{B.10}$$

where W and V are in arbitrary units, and s is the slope of the W-V curve in the shrinking period (if W and V are in consistent units, $s = \rho_l$, the liquid density).

B.III.3 Experimental details

Drops of finely ground zinc-oxide slurry (ZnO particle size $\leq$ 1 μm) were suspended by means of a hypodermic syringe at the tip of a 30 to 40 mm section of 46-gauge (0.061 mm diameter) copper wire. Drop sizes varied from 0.8 to 2 mm diameter. The copper wire was clamped to a microscope mechanical stage mounted on a support in such a manner that fine horizontal and vertical displacements of the wire could be made.

Photographs of the drops were taken with a 35 mm camera fitted with a 1:3.5/35 lens at the end of a 200 mm extension bellow . Both camera and mechanical stage support were securely mounted on a common platform. Each drop was photographed under a floodlight against a dark background, at intervals of 1 minute. The drops were evaporating in quiescent air at room temperature and no attempt was made to control the evaporation conditions. The total change in wire deflection ranged from 10 to 40 mm.

A sevenfold magnification was obtained on the negative. The final enlargement gave a total magnification of about 50. Because the drop or particle shape was not completely spherical, the cross-section area of the drop was measured with a planimeter and from this the diameter could be calculated. For liquid droplets, symmetry about a vertical axis was assumed, while for elongated consolidated particles, symmetry about an axis parallel to the supporting wire was assumed (figure 4).

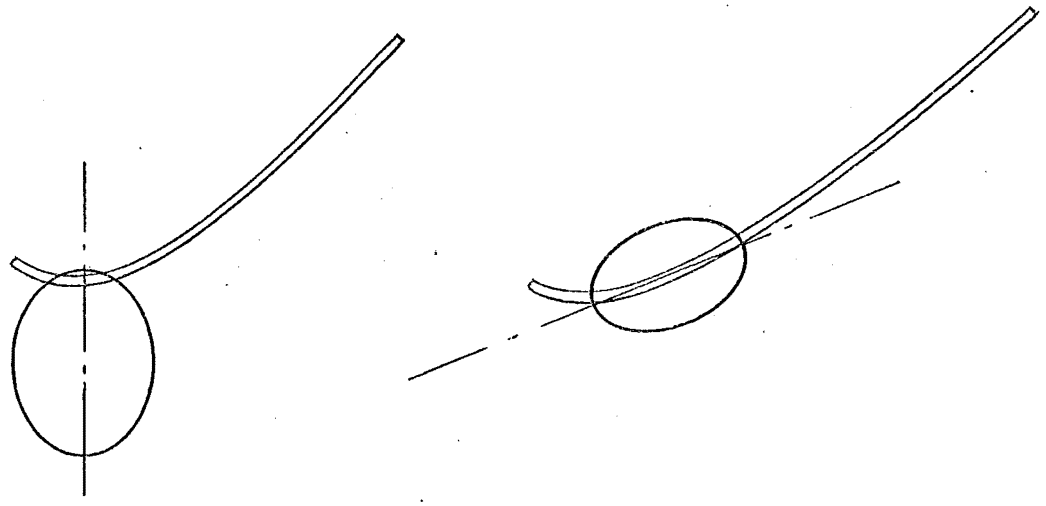


FIGURE B.4 : DEFORMATION OF SUSPENDED DROP & PARTICLE

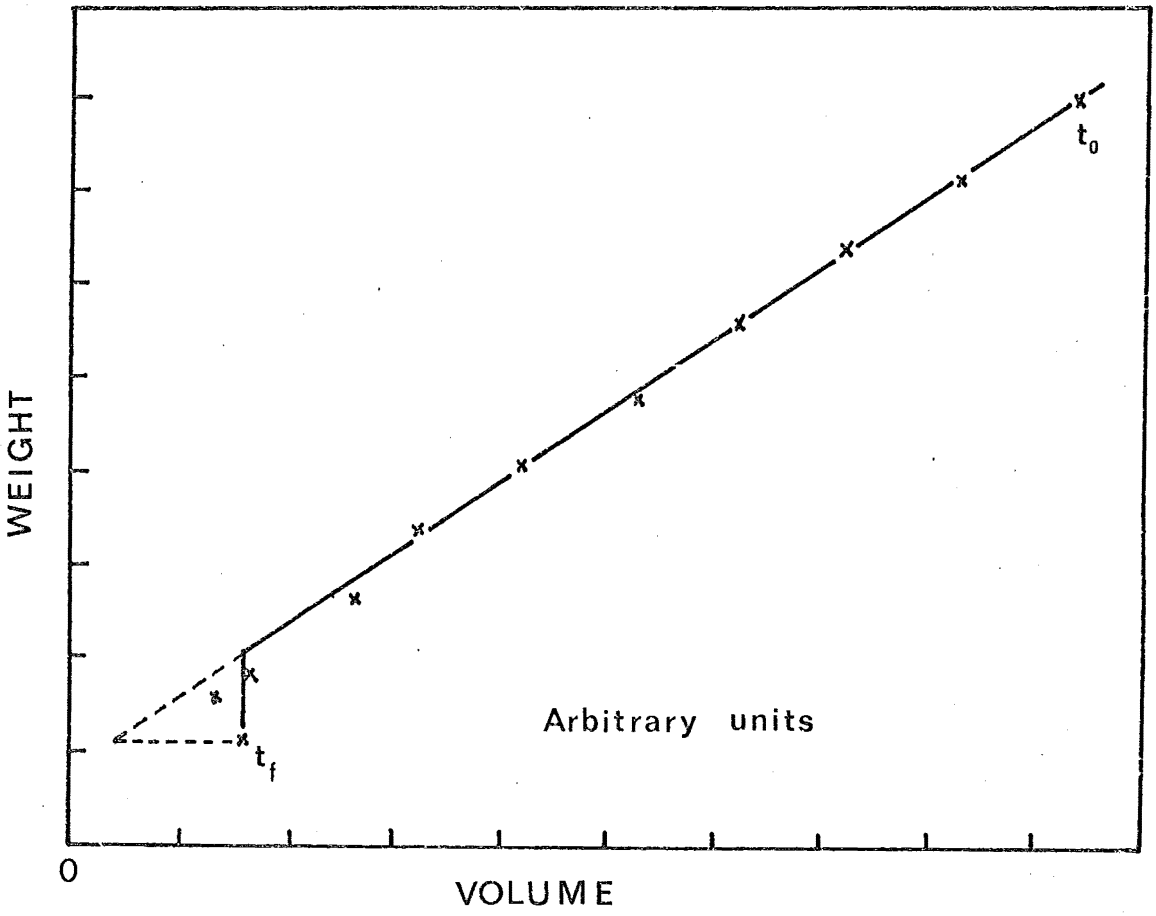


FIG. B5: WEIGHT-VOLUME PLOT FOR ZnO SLURRY

B.III.4 Results

A typical weight-volume graph for the zinc-oxide slurry is shown in figure 5. It can be seen that the simple two-period model holds fairly well, although the separation between the two periods is not quite sharp, indicating that some gradual consolidation takes place in the real situation. Also, some "over-shrinkage" occurs, the volume shrinking to below its final value V_f and then expanding again. This is probably due to the surface-tension forces exerted by the moisture when in the pendular (wedge-shaped) state between the particle of solids. These forces tend to pull the particles together (figure 6). Assuming that the mean ZnO particle diameter is 1 μm, a force balance based on figure 6 showed that surface-tension forces can exert an equivalent pressure of up to 2.4×10^5 Pa , or 2.4 atmospheres.

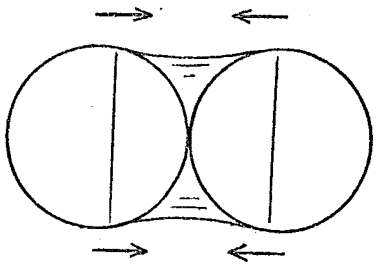


FIGURE B.6: SURFACE-TENSION FORCES EXERTED BY MOISTURE

The results of all runs have already been plotted as the final void fraction vs the initial liquid volume fraction in figure 3 of chapter 5.

Notation for appendix B.III

D	droplet or particle diameter [m]
s	slope of the weight-volume plot in the free shrinking period [N/m^3]
V	drop or particle volume [m^3]
W	drop or particle weight [N]
ε	liquid volume fraction or void fraction [-]

Subscripts:

c	critical, or consolidation
f	final, or dry particle
i	initial
s	solid

B.IV AN ATTEMPTED SIMULTANEOUS MEASUREMENT OF EVAPORATION AND RESIDENCE TIME

B.III.1 Aim of the experiment

To measure the degree of evaporation of droplets against their residence time in the spray drying chamber.

B.III.2 Background and theory

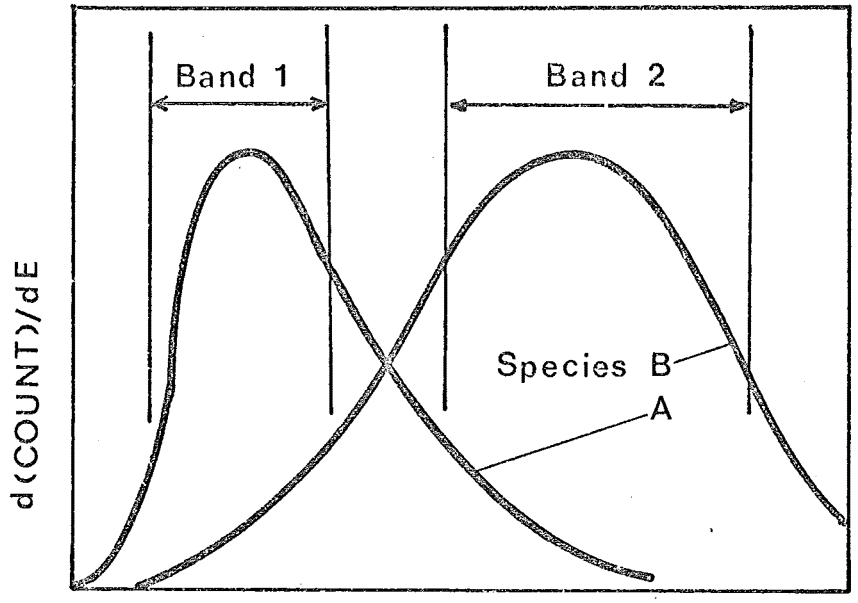
In chapter 6 of this thesis, we have seen that the spray residence time distribution has an important effect on the dryness of the product. If it was possible to know directly the evaporation as a function of residence time, this effect could be predicted and the performance of the spray dryer could be calculated with great accuracy.

The method whereby it was intended to measure these variables is by double-labelling the spray: a non-evaporating tracer can be used to measure residence times (as described in chapter 4), while a tracer evaporating with water can be used to measure evaporation.

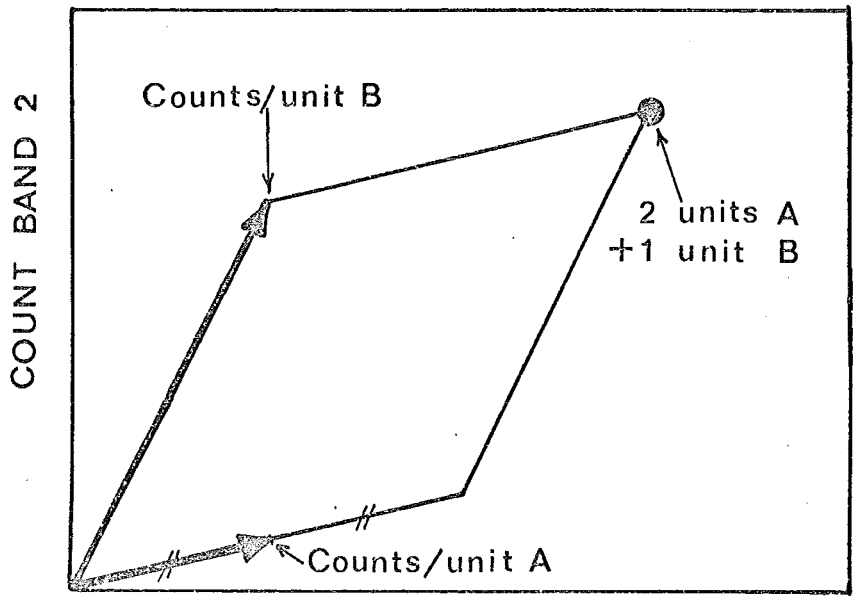
The principle of double-label counting radioactive materials using a scintillation counter has been described by Bush (1). In scintillation counting, each radioactive species produces pulses with a specific energy spectrum (figure 7a). If counting is done within two energy bands, the ratio of the number of pulses counted in band 1 and band 2 will depend upon the species. Figure 7b gives a vectorial illustration of the method whereby the activities of two species can be measured simultaneously.

B.III.3 Experimental details

A saturated sodium-chloride solution was sprayed into the drying chamber. Tritium (^{3}H) as H_2O was used to label the water, and ^{14}C as $NaHCO_3$ was used to label the salt. A pulse containing about 10 µC of ^{14}C and 50 µC of ^{3}H was injected into the nozzle at time 0.



(a)



(b)

FIG. B6: PRINCIPLE OF DOUBLE-LABEL COUNTING

The droplets were collected at the outlet of the spray dryer by a travelling droplet catcher as described in chapter 4. However, the collecting cells in this experiment were not covered with glass filter paper, but were filled with a collecting liquid and tightly wrapped around the side and at the bottom with thin, impervious P.T.F.E. tape. A small piece of brass was placed in each cell to facilitate the emptying of the cell.

Bench tests were carried out to find the best collecting liquid, i.e. one that would absorb the droplets or cover them so that evaporation from the cell is minimised. In these bench tests, both tracers were injected into cells filled with the collecting liquid being tested, and the activities were counted after various time intervals. Toluene, n-decane, a stable suspension of toluene-Triton X-100 - water (the liquid scintillant described in chapter 4) and a saturated lithium-chloride solution were tested; the last one was finally chosen.

After the droplets had been collected into the cells these were unwrapped, placed into counting vials, the vials were shaken and counted for both ^{3}H and ^{14}C as described before.

B.III.4 Results and discussion

Only one run was carried out, at operating conditions corresponding to those of the spray residence time distribution experiment, run A3 (chapter 4, table 1).

An entirely unexpected result showed up: instead of the $^{3}H/^{14}C$ ratio decreasing with residence time (because tritium is evaporating while ^{14}C is not), this ratio was found to increase with time and even exceed the ratio in the injected tracer pulse (figure 8).

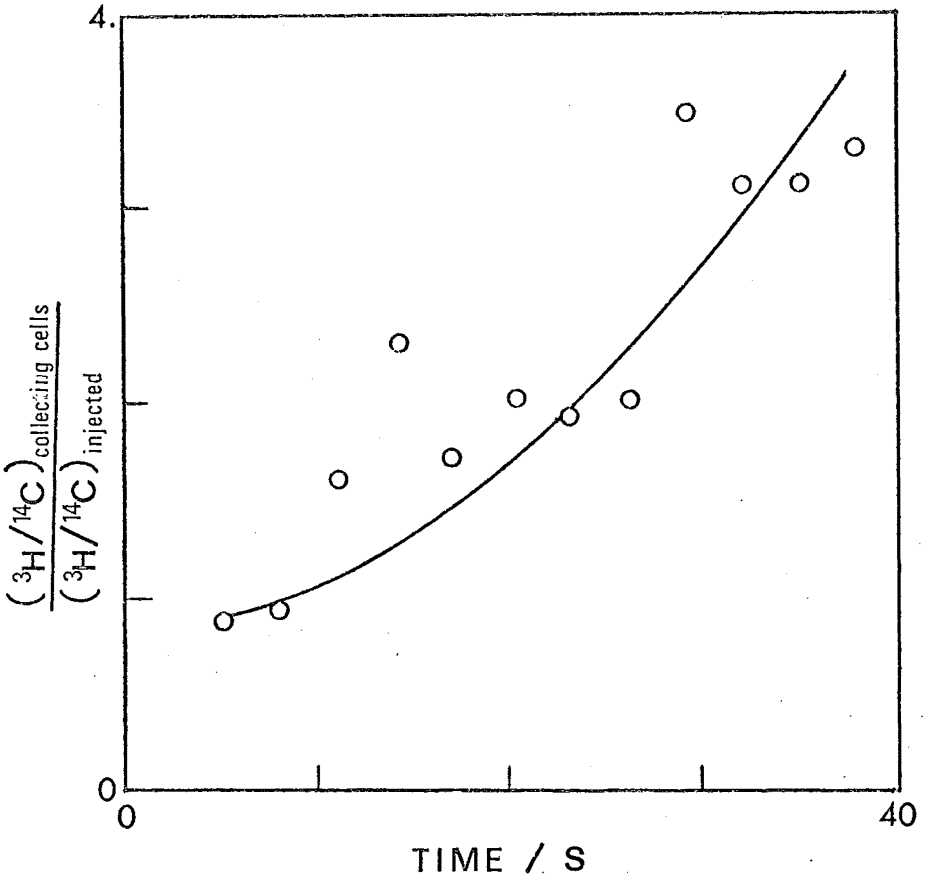


FIGURE B8: 'EVAPORATION' VS RESIDENCE TIME

The explanation for this phenomenon is that evaporation is not a one-way process but the net result of interchange of water molecules between the droplets and the air. Thus some tritiated water molecules were transferred from the droplets to the air, then re-entered droplets which had a higher residence time or which were injected into the drying chamber at a later time, thus increasing the $^3H/^{14}C$ ratio.

This failure illustrates the need for careful theoretical investigation before starting any experiment.

Reference

(1) Bush E.T., Anal. Chem. 36, 1082 (1964)

APPENDIX C

OPERATING PROCEDURES FOR THE TWO-STAGE SPRAY DRYER

In the following sections valves identification numbers are shown on the flow diagram, Figure 3 of Chapter 1.

I. "COLD" RUN, AIR FLOW ONLY:

I.1 - Preparation:

1. Fill in the operating sheet (Figure C1).
2. Check that no leak is present.
3. Isolate the two stages by ensuring that the rotary valve is in the "off" position, and close valve V7.
4. If the second stage is not required, close valves V3, V4 and V8 to isolate this stage.
5. If the second stage is required : open valves V3 and V4 full; ensure that the control valve CV2 is fully open and its actuator turned off; open valve V8 fully; close the butterfly valve V5 by lowering its lever, besides the cooler-scrubber.
6. Open valves V1 and/or V2 depending on the flowrate required.
7. Ensure that the pressure drops across the two pitot tubes (for the 100 mm main inlet pipe and for the 25.4 mm busbar box inlet pipe) are not excessive for the manometers used.
8. Set blower gearbox, according to the graph of Figure C3. Use third or fourth gear to avoid slow pulsations.
9. Fully open valve V14.
10. Set bypass valve V15 according to flowrate required. If inexperienced in using the spray dryer, open V15 fully, then close it slowly once blower has been started.

I.2 - Turn-on Procedure:

1. Go through the check-list (Figure C2).
2. Turn the blower on.
3. Adjust valves V1 and/or V2 and/or V15 until the flowrate required for the first stage is obtained.
4. If the second stage is required : adjust valves V3, V4 and V8 until the flowrate required for the second stage is obtained.

I.3 - Turn-off Procedure:

Turn the blower off.

II. "HOT" RUN, AIR FLOW ONLY:

II.1 - Preparation:

1. Go through the procedure described in Section I.1.
2. Set the control temperature of the steam heater on the temperature controller TC1.
3. Open the busbar box and connect the number (multiple of 3) of elements required. Check that all connectors are secure. Close busbar box.
4. If the second stage is required : set the temperature controller TC2.
5. Clean the psychometer wet bulb and check their distilled water supply if required. CAUTION: The water level must be such that the wet bulb is just wet, not dry or overflowing.
6. Connect the required thermocouple terminals required to the 12-point recorder at the connecting board besides the control panel.
7. Ensure that the thermocouple cold junctions are at $0^{o}C$.

8. Ensure that the bleed valve V16 (for the probe of controller TC1) is fully open.

II.2 - Turn-on Procedure:

1. Go through check list.
2. Turn blower on.
3. Readjust the flow through the first stage as in Section I.2.
4. Readjust the flow through the second stage as in Section I.2. Check the flow in the first stage.
5. Turn the temperature controllers on at the control panel.
6. Turn electric heater on if required.
7. Turn steam heater on very slowly by opening valve V12.
8. If required, turn the LiCl cells on.
9. If required, turn humidifying steam on by opening valves V9 and V11, and adjusting valves RV1 and V10.
10. Open the bleed valves associated with the humidity measuring devices H1, H2, H3, H4 until suitable flow rates are obtained (less than 0.5 m/s past the LiCl cells, at least 3 m/s past the psychometers). Ensure that the air temperature in the line from the column to the humidity measuring devices does not drop below the dew point.

II.3 - Turn-off Procedure:

1. Turn off electric heater.
2. Turn off heating steam.
3. Turn off humidifying steam.
4. When temperatures in system have dropped below 60^{o}C, turn off blower.
5. Turn off the recorder and the LiCl cells.

III. "HOT" RUN WITH SPRAYING OF FEED: (Using a two-fluid atomiser).

III.1 - Preparation:

1. Go through the procedure described in Section II.1.
2. Ensure that the proper nozzle is installed, the feed and the atomising air lines are connected, and the pressure equalising line is installed.
3. Ensure that a cyclone of the proper size is used as Cyclone 1. (see Chapter 1)
4. If the second stage is used : ensure that the rotary valve is clean, check that its speed is about 100-120 rpm, open fully valve V7 and close valve V6 , install a receiver under Cyclone 2. CAUTION: Dirt will cause leaks and damage the Rotary valve.
5. If the second stage is not used : install a product receiver at the base of Cyclone 1.
6. Check the working conditions of the pneumatic vibrators at the base of Cyclone 1 and at the bends of the second stage, the nozzle cleaner solenoid and its circuit, the intermittent valve V13 and its circuit, the air cooler for the solenoid of Valve V13.
7. If a high air rate (greater than 0.4 m/s in the drying chamber) is used, remove packing from the cooler scrubber.
8. Install filter bag if required.

III.2 - Turn-on Procedure:

1. Go through the procedure described in Section II.2.
2. Turn on the rotary valve.
3. Turn on the nozzle cleaner, the intermittent valve V13, the air cooler for the solenoid of V13, the pneumatic vibrators.

4. Turn on the cooler-scrubber water using a low flow rate (about 1 turn). CAUTION: Ensure that flow is not excessive, causing flooding of the plates in the cooler or flowback into Cyclone 1 and the rotary valve.

5. Turn on the atomising air and the feed pump, and adjust the feed rate.

6. Check temperatures and flowrates, and readjust if necessary.

III.3 - Turn-off Procedure:

1. Turn off feed flow to nozzle. Turn off atomising air.

2. Turn off humidifying steam.

3. After twenty minutes, turn off heaters.

4. Turn off vibrator and intermittent valve V13. Turn off air cooler for V13.

5. Turn off rotary valve.

6. Turn off cooler-scrubber.

7. When temperatures in system have dropped to below $60^{\circ}C$, turn off blower.

8. Turn off recorder and LiCl cells.

FIGURE C1

DATE:
RUN:
TIME ON:
TIME OFF:

SPRAY DRIER OP. SHEET

NOZZLE
Dvs/μm:
Nozzle No.:
Air P/psig:
Liq. head/in:
Air rota/cm:
Liq.rota/cm:
Slurry concn/% solid:
Mean final ptcle size/μm:
Final density:
Initial feed level:
Final feed level:

EVAPN CONDITIONS
$T_{air}-T_{wb}/^{o}C$:
Air humidity:
$T_{air}/^{o}C$:
$T_{wb}/^{o}C$:
Time for 100% evap:
99% evap:
95% evap:

ROTARY VALVE
Bottom rota rdg:
Top rota rdg:
Speed/rpm

MANOMETERS
Busbars cooling pitot:
Balance hot/cold air:
Across 1st cyclone:
Across 2nd cyclone:
Across 2nd stage:
Across cooler:

1ST STAGE AIR
$T/^{o}C$:
Humidity:
Vel/m s^{-1}
Air Res. Time/s:
Blower gear:
Bypass:
Butterfly valve:
Pitot rdg/cm:
Cyclone No.:

2ND STAGE AIR
No. of sections (3/1)
Air rate, top rota rdg:
Rate/kg s^{-1}:
T control setting/C:
T bottom/C:
T top/C
Vel/m s^{-1}:
Res. time/s:

HEATERS
Final T/C:
Steam hter setting/C:
Elec heater:
T rise/C:
Power/kW:
No. elements:

PRODUCT
Weight:
Size:
Moisture:

FIGURE C2

CHECK LIST

MANOMETERS: connected/isolated

12-PT RECORDER IDENTIFIED:

1/	2/	3/
4/	5/	6/
7/	8/	9/
10/	11/	12/

MAIN AIR STREAM:

Gearbox set:

Bypass set:

Main gate valve set:

Blower on:

Butterfly valve set:

Pitot tube read:

2ND STAGE:

No. of sections set:

Inlet valves set:

Outlet valve open/shut:

Rotameter read:

ROTARY VALVE:

Speed set:

Flows set:

Motor on:

12-POINT RECORDER:

Thermos filled:

Recorder on:

Date entered:

HEATING SYSTEM:

Modulating valves on:

Control temperatures set:

Steam on:

Elements set:

Busbar cooling air on/off:

Electric heater on:

HUMIDIFICATION

1st stage humidification steam on:

2nd stage humidification steam on:

LiCl cells on:

Hygrometers cleaned and filled:

AUXILIARY EQUIPMENT:

Cooler-scrubber on:

Cooling-water on:

Vibrator on:

Pulsing valve on:

"Hair dryer" on:

EQUILIBRIUM T REACHED

LINES CLEARED

NOZZLE:

Cleaner on/checked:

Initial feed level recorded:

P. equalising line on:

Stirrer on:

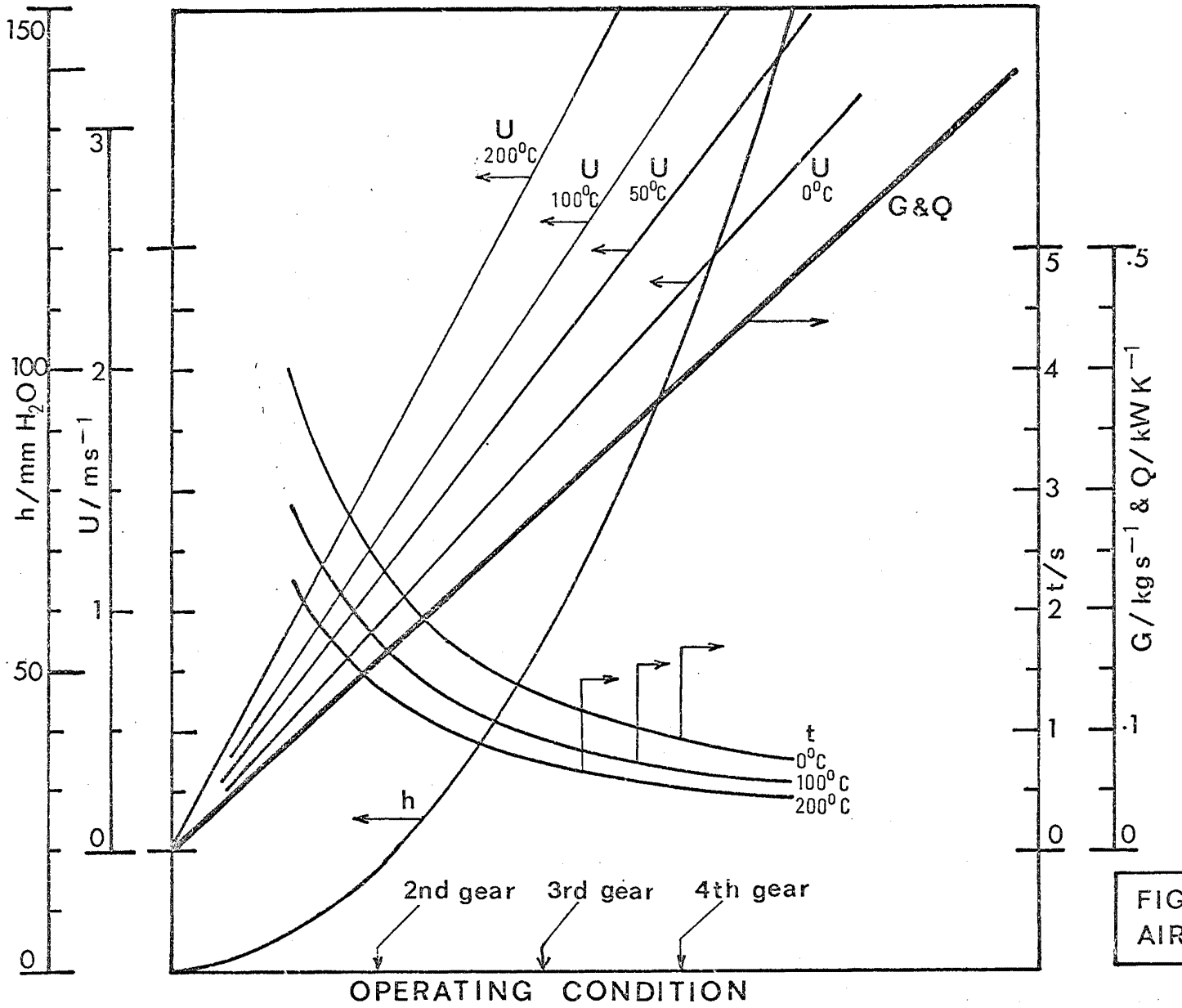
Air on:

Line opened, time:

TIME SPRAYING STOPPED:

FINAL FEED LEVEL RECORDED:

PRODUCT WEIGHED:



h = 4" inlet Pitot tube reading

G = mass air rate

Q = heat required for 1 K raise

U = air velocity in dryer

To find approximate settings, draw a vertical line through the desired operating condition .

FIG. C3 : SPRAY DRYER AIRFLOW SETTINGS

APPENDIX D

LISTING OF COMPUTER PROGRAM FOR EVAPORATION CALCULATION IN COCURRENT SPRAY DRYERS

```
C EVAPORATION IN COCURRENT SPRAYDRYER WITH PRESSURE OR PNEUMATIC NOZZLE 00002000
C VERSION 3                                                            00003000
C EXTENSION OF PROG. OF 13-MAY-74 AND 27-JUN-75                        00004000
C                                                                      00005000
C                                                                      00006000
C ***********************************************************************00007000
C                                                                      00008000
C THEORY                                                               00009000
C                                                                      00010000
C                                                                      00011000
C ASSUME HYDRODYNAMIC PROFILE IS DIVIDED INTO 2 ZONES:                 00012000
C  1/ JET ZONE,GOVERNED BY JET DYNAMICS,WHOSE MASS FLOW,VEL.,TEMP. AND 00013000
C HUMIDITY PROFILE IS CALC. IN SUBROUTINE "PROFIL"                     00014000
C IN THIS ZONE MOMENTUM BALANCE IS NOT NEGL. FOR THE AIR               00015000
C THIS ZONE MAY INCLUDE A TRANSITION WHERE PROFILES CHANGE LINEARLY    00016000
C WITH DISTANCE FROM JET TO MAIN ZONE CHARACTERS                       00017000
C  2/ MAIN ZONE,WHICH DEPENDS ON THE DRYER,WHOSE MASS FLOW ETC...      00018000
C PROFILE ARE CALC. IN SUBROUTINE "PROFI1"                             00019000
C AT START OF THIS ZONE ALL DROPLETS ARE AT SETTLING VEL.              00020000
C BY DEFAULT ASSUME A LINEAR TEMPERATURE PROFILE IN MAIN ZONE DUE TO   00021000
C WALL HEAT LOSS,IN THE ABSENCE OF EVAPORATION                         00022000
C IN ADDITION A TRANSITION ZONE WITH LINEAR GRADIENTS MAY BE           00023000
C INSERTED BETWEEN THE PREVIOUS 2 ZONES                                00024000
C                                                                      00025000
C NB BY CHANGING PROFIL&PROFI1 CAN ACCOMODATE ANY FLOW REGIME,HT LOSS...00026000
C                                                                      00027000
C THE VELOCITY,TEMPERATURE & CONCENTRATION PROFILE IN A JET CAN BE     00028000
C FOUND IN ABRAMOVITCH,"THEORY OF TURBULENT JETS"                      00029000
C THE EFFECTIVE TEMPERATURES,VELOCITIES ETC... IN A JET ARE CALCULATED 00030000
C INTHESIS                                                             00031000
C ENTRAINMENT OF AIR INTO JET IS CALCULATED BY DAVIES                  00032000
C                                                                      00033000
C EVAPORATION FROM DROPLETS FOLLOW RANZ & MARSHALL EQN                 00034000
C NU=2.+0.6*RE**0.5*PR**0.5                                            00035000
C                                                                      00036000
C EFFECT OF MASS TRANSFER ON HEAT TR. GIVEN BY (1/(1+B))               00037000
C WHERE B=SPEC.HT*TEMP.DIFFERENCE/LATENT HEAT                          00038000
C                                                                      00039000
C ASSUME THAT DROPLET EVAPORATION COMPRISES 2 PERIODS:                 00040000
C 1ST PERIOD:DROPLET SHRINKS FREELY                                    00041000
C 2ND PERIOD:(AFTER WCRIT,ECRIT,DCRIT) CRUST FORMS,SHRINKING CEASAS    00042000
C DROPLET DENSITY FALLS                                                00043000
C                                                                      00044000
C STD DRAG CURVE IS APPROXIMATED SEGMENTWISE                           00045000
C                                                                      00046000
C ADIABATIC-SATURATION TEMPERATURE&HUMIDITY OF EVAPORATING SOLUTION    00047000
C ARE CALCULATED IN SUBROUTINE WBULB                                   00048000
C                                                                      00049000
C EFFECT OF TURBULENCE:CALC. RELATIVE VEL. DUE TO TURBULENCE AS LEVIN & 00050000
C GLASTONBURY,THEN ADD VECTORIALLY TO MEAN REL.VEL..FROM THIS COMBINED 00051000
C VEL FIND RE,DRAG,NUSSELT NO.                                         00052000
C                                                                      00053000
C APPROX. TERMINAL VEL AT START OF MAIN ZONE CALC FROM SMITH           00054000
C                                                                      00055000
C EFFECT OF RADIATION EITHER FOLLOWS TREATMENT IN THESIS(ASSUMING      00056000
C UNIFORM RADIATION) OR HOTTEL&COHEN TREATMENT(SEE DEFINITION OF RADCAL)00057000
C                                                                      00058000
C                                                                      00059000
C                                                                      00060000
C CALCULATION METHOD                                                   00061000
C                                                                      00062000
C                                                                      00063000
C AT EACH POINT IN SPACE,CALCULATE THE VELOCITIES AND EVAPORATIONS      00064000
C FOR EACH SIZE RANGE                                                  00065000
C ADD UP OVER ALL SIZE RANGES                                          00066000
C FIND EFFECT ON AIR VELOCITY,TEMPERATURE AND HUMIDITY                 00067000
C RECALCULATE SPRAY VELOCITY AND EVAPORATION BASED ON THE CORRECTED    00068000
C AIR CONDITIONS,ETC... UNTIL GET CONVERGENCE ("TEST" & "DAM"<.01)     00069000
C ITERATION IS ACCELERATED BY USING THE WIGHTING FACTORS H FOR         00070000
C EVAPORATION AND HV FOR SPRAY VELOCITY                                00071000
C WHEN CONVERGENCE IS REACHED,GO ON TO THE NEXT POINT                  00072000
C                                                                      00073000
C FOR DROPLET SURFACE TEMPERATURE,FILM TEMP.,FILM PROPERTIES,USE VALUES 00074000
C AT PREVIOUS POSITION                                                 00075000
C FOR DROPLET SIZE&DENSITY,AIR TEMP.,AIR VEL.,CORRECT DURING ITERATIONS 00076000
C                                                                      00077000
C THE EQUATION OF MOTION EXPRESSES THE RATE OF CHANGE OF SQUARED       00078000
C VELOCITY OF EACH DROPLET WRT DISTANCE                                00079000
C FOR VERY SMALL DROPLETS(TERMINAL REYNOLDS NO<1)ASSUME REL.VEL. IN    00080000
C MAIN ZONE FOLLOWS STOKES EQN                                         00081000
C THE EQN OF EVAPORATION EXPRESSES THE RATE OF CHANGE OF  REL.EVAPORATN 00082000
C WRT DISTANCE                                                         00083000
C                                                                      00084000
C RUNGE-KUTTA METHOD OF ORDER 4 IS USED IN SOLVING THE EQUATION OF     00085000
C MOTION AND EVAPORATION                                               00086000
C                                                                      00087000
C                                                                      00088000
C                                                                      00089000
C ***********************************************************************00090000
C                                                                      00091000
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C                                                                       00092000
C  NOTATION                                                             00093000
C                                                                       00094000
C                                                                       00095000
C  AK1,AL1,AK2,AL2...=INCREMENTS IN ESIZE(J)&W(J) FOR RUNGE-KUTTA       00096000
C  AM=MEAN VEL. FOR WHOLE SPRAY AT A CERTAIN DISTANCE,M/S               00097000
C  AMOLD=OLD AM,M/S                                                     00098000
C  AMSIZE(J)=LOCAL VELOCITY FOR J-TH SIZE RANGE,M/S                     00099000
C  NB:AM,AMSIZE INCLUDE THE MOMENTUN OF EVAPORATED LIQUID               00100000
C  ANOZ:IF(ANOZ.GT.0.)PNEUMATIC NOZZLE,OTHERWISE PRESSURE NOZZLE        00101000
C  ATP=INVERSE PARTICLE TIME CST,/S                                     00102000
C  CDRESQ=DRAG COEFT.*TERMINAL REYNOLDS NO. SQUARED                     00103000
C  CDRT=TERMINAL DRAG FROM SMITH                                        00104000
C  CF=FEED SPECIFIC HEAT,J/KGK                                          00105000
C  COEFF2=CONSTANT COEFFICIENT IN THE EVAPORATN EQN=6/HTLAT/WLIQ/DENSLO  00106000
C  COND=CONDITION THAT(ITER.GT.16)                                      00107000
C  COND1=CONDITION FOR CONVERGENCE                                      00108000
C  CPGAS=AIR SPECIFIC HEAT,J/KG K                                       00109000
C  CRAD=RADIATION FLUX TO DROP/(RADIOS-TWB**4),W/M2K2                   00110000
C  CS=ADIABATIC SATURATED AIR SPECIFIC HT,J/KGK                         00111000
C  CSJ(J)=SPECIFIC HEAT OF AIR+WATER VAPOUR AT DROP SURFACE,J/KG.K      00112000
C  CSS=CSJ(J)                                                           00113000
C  DAM=RELATIVE CHANGE IN SPRAY MOMENTUM                                00114000
C  DCR(J)=CRUST FORMING DIAMETER,M                                      00115000
C  DCRIT=CRUST FORMING DIAMETER,M                                       00116000
C  DEN(J)=DROPLET DENSITY,KG/M3                                         00117000
C  DENLIQ=DENSITY OF LIQUID IN FEED,KG/M3                               00118000
C  DENOLD(J)=VALUE OF DEN(J) AT PREVIOUS POSITION                       00119000
C  DENS=LOCAL AIR DENSITY,KG/S                                          00120000
C  DENSL=DENSITY OF DROPLET BEING CONSIDERED,KG/M3                      00121000
C  DENSLO=INITIAL DROPLET DENSITY,KG/M3                                 00122000
C  DENSOL=DENSITY OF SOLID IN FEED,KG/M3                                00123000
C  DER=DERIVATIVE OF SATURATION CURVE OF WATER,/K                       00124000
C  DHY=HYDRAULIC DIAMETER OF DRYER=4*VOL/WALL AREA,M                    00125000
C  DISTAN=DISTANCE FROM NOZZLE AT WHICH CALCULATIONS ARE TERMINATED,M   00126000
C  DN=MATRIS OF NUMBER OF DROPLETS IN EACH SIZE RANGE                   00127000
C  DOLD(J)=VALUE OF D(J) AT PREVIOUS POSITION                           00128000
C  DRAG=SUBFUNCTION CALCULATING DRAG COEFFICIENT                        00129000
C  DVOL(J)=INITIAL VOLUME FRACTION OF J-TH SIZE RANGE                   00130000
C  DX1=DISTANCE INCREMENT IN JET ZONE,M                                 00131000
C  DX2=DISTANCE INCREMENT IN MAIN ZONE,M                                00132000
C  DO=MATRIX OF VALUES OF INITIAL DROPLET DIAS FOR EACH SIZE RANGE,M    00133000
C  D32(I)=SAUTER MEAN DIAMETER,M                                        00134000
C  E(I)=FRACTION OF SPRAY EVAPORATED                                    00135000
C  ECRIT=FRACTION EVAPORATION AT WHICH CRUST FORMS                      00136000
C  EMAX=MAX.POSSIBLE EVAPORATION                                        00137000
C  EMIS=MEAN ABSORPTIVITY OR EMISSIVITY OF DROPLETS IN DRYER            00138000
C  EMIW=EMISSIVITY OF WALL                                              00139000
C  ESOLD(J)=OLD VALUE OF ESIZE(J)                                       00140000
C  ESIZE(J)=FRACTION EVAPORATED FOR J-TH SIZE RANGE (LOCAL)             00141000
C  EXC=EXTINCTION COEFFT FOR RADIATION INTO CLOUD=PROJECTED AREA OF DROPS00142000
C  PER UNIT VOL,/M                                                      00143000
C  EOO=TOTAL EVAPORATION TO DATE NOT DUE TO DROPLET OVERHEAT            00144000
C  FAC=RELATIVE DRYING RATE AS COMPARED WITH DROPLET OF LIQUID SOLUTION  00145000
C  FCL=EFFECTIVE ABSORPTIVITY OF CLOUD OF DROPLETS AS A WHOLE           00146000
C  FCURVE=SUBFUNCTION TO CALC. FAC                                      00147000
C  FE=FRACTION UNEVAPORATED FOR WHOLE SPRAY                             00148000
C  FSIZE=1-ESIZE(J)                                                     00149000
C  FO=LIQUID MASS FEED RATE,KG/S                                        00150000
C  F1=SUBFUNCTION CALCULATING THE DERIVATIVE OF W(J) VS DISTANCE        00151000
C  F2=SUBFUNCTION CALCULATING THE DERIV. OF ESIZE(J) VS DISTANCE        00152000
C  G(I)=AIR MASS RATE INCLUDING ENTRAINED AIR,KG/S                      00153000
C  GEXT=MASS RATE OF EXTERNAL AIR FLOW,KG/S                             00154000
C  GO=ATOMISING AIR MASS RATE,KG/S                                      00155000
C  HAJ=JET HALF ANGLE,DEG(DEFAULT VALUE=12.4)                           00156000
C  HCW=HTLAT*WLIQ/CF,K                                                  00157000
C  HRATIO=FO*WLIQ*HTLAT/CPGAS=TEMP. FALL CAUSED TO UNIT MASS RATE OF AIR 00158000
C  BY TOTAL EVAPORATION OF FEED,K KG/S                                  00159000
C  HTLAT=HEAT OF EVAPORATION OF LIQUID,J/KG                             00160000
C  I=INDEX REFERRING TO POSITION                                        00161000
C  J=INDEX REFERRING TO SIZE RANGE                                      00162000
C  JEV=NO. OF SIZE RANGES COMPLETELY EVAPORATED                         00163000
C  NPT=NUMBER OF POINTS IN SPACE CONSIDERED                             00164000
C  NP1=NO.OF PTS FROM ORIGIN TO XTRA INCLUSIVE                          00165000
C  NP2=NO.OF PTS FROM XTRA(EXCLUSIVE) TO XEND(INCLUSIVE)                00166000
C  NP3=NO.OF PTS FROM ORIGIN TO XJET INCLUSIVE                          00167000
C  NSIZE=NO. OF SIZE RANGES(TO BE SUPPLIED BY "SPRAY")                  00168000
C  PRINT1=DISTANCE INCREMENTS FOR PRINTOUT,JETZONE,M                    00169000
C  PRINT1=DISTANCE INCREMENTS FOR PRINTOUT,MAIN ZONE,M                  00170000
C  PROFIL=SUBROUTINE CALCULATING THE VELOCITY,TEMPERATURE ETC...        00171000
C  PROFILE IN THE JET (& TRANSITION) ZONE                               00172000
C  PROFI1=SUBROUTINE CALCULATING THE PROFILES IN THE MAIN ZONE          00173000
C  QRCP1=1+RADIANT HT/CONVECTION HT                                     00174000
C  RADCAL=PARAMETER IDENTIFYING METHOD OF RADIATION CALCN               00175000
C  IF RADCAL=0.,NO RADIATION CALCULATION                                00176000
C  IF RADCAL<0,ASSUME UNIFORM RADIATION&USE METHOD IN THESIS            00177000
C  IF RADCAL.GT.0,USE HOTTEL&COHEN METHOD.WRAD(I),I=1,40  MUST THEN     00178000
C  BE READ FROM CARDS                                                   00179000
C  RATE(J)=MEAN EVAPORATION RATE=ESIZE(J)/RTI(J),/S                     00180000
C  RCP1(J)=1+RADIANT HT/CONVECTION HT                                   00181000
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C RJET=JET RADIUS,M                                                     00182000
C RS=RELATIVE HUMIDITY OF AIR IN EQUIL. WITH EVAPORATING SOLUTION       00183000
C RTI(J)=REIDENCE TIME OF J-TH SIZE DROPLETS,S                          00184000
C RTIME=A MEAN RESIDENCE TIME OF DROPLETS,S                             00185000
C SE=DROPLET EVAPN RATE/EVAPN RATE WITH DROPLET OVERHEAT NEGLECTED      00186000
C SET=SPRAY EVAP RATE/EVAPN RATE WITH SPRAY OVERHEAT NEGLECTED          00187000
C SH=SHIELDING FACTOR FOR RADIATION FROM WALL TO DROPS                  00188000
C SHA=HEAT CAPACITY OF ATOMISING AIR,J/K                                00189000
C SHF=HEAT CAPACITY OF FEED,J/K                                         00190000
C SPRAY=SUBROUTINE CALCULATING THE DROPLET SIZE NUMBER DISTRIBUTN       00191000
C SQVRT=VRTSQ(J),M2/S2                                                  00192000
C T(I)=JET AIR EFFECTIVE TEMP.,CORRECTED FOR EVAPORATION,DEG.K          00193000
C TAV=MEAN FILM TEMP. AROUND DROPLETS AT PREVIOUS POINT,DEG.K           00194000
C TDR(J)=DROPLET MEAN TEMPERATURE,K                                     00195000
C TEST=RELATIVE CHANGE IN EVAPORATN BW ITERATIONS                       00196000
C TEXT=TEMPERATURE OF EXTERNAL AIRFLOW,DEG.K                            00197000
C TF=FEED TEMPERATURE,K                                                 00198000
C TFALL=FALL IN AIR TEMPERATURE DUE TO EVAPORATION,K                    00199000
C THCOND=LOCAL AIR THERNAL CONDUCTIVITY,W/M K                           00200000
C TINIT(I)=JET AIR EFFECTIVE TEMP. WITHOUT SPRAY,DEG.K                  00201000
C TLOSS=DECREASE IN AIR TEMP.PER UNIT LENGTH DUE TO WALL LOSS,K/M       00202000
C TS(J)=TWB=SURFACE TEMP. OF DROPLET IF DROPLET HEAT NEGLECTED,K        00203000
C TUIN(I)=SQUARED TURBULENT VEL. OF AIR,M2/S2                           00204000
C TUINO=TUIN AT TOP OF DRYER,M2/S2                                      00205000
C TUINI=TUIN AT BOTTOM OF DRYER,M2/S2                                   00206000
C TUSC(I)=LAGRANGIAN TIME SCALE OF TURBULENCE,S                         00207000
C TUSCO=TUSC AT TOP OF DRYER,S                                          00208000
C TUSCI=TUSC AT BOTTOM OF DRYER,S                                       00209000
C TW=EQUILIBRIUM TEMPERATURE OF AIR&FEED EMERGING FROM NOZZLE,K         00210000
C TWA=MEAN RADIATING TEMP. OF WALL,K                                    00211000
C TSAVE =   MASS AVERAGE OF THE SURFACE TEMPETATURES OF DROPLETS IN     00212000
C SPRAY,FOR PURPOSE OF CALC. THE FILM PROPERTIES,DEG.K                  00213000
C TO=TEMPERATURE OF ATOMISING AIR,DEG.K                                 00214000
C TO WILL BE RECALC. TO GIVE HYGROTHERMAL EQM WITH FEED                 00215000
C VAIR(I)=AIR VEL. IN JET,CORRECTED FOR LOSS OF MOMENTUM TO SPRAY,M/S   00216000
C VELOUT=EMERGING LIQUID VELOCITY,M/S                                   00217000
C VDROPS=DROPLET VELOCITY AVERAGED OVER ALL SIZES,M/S                   00218000
C VINI(I)=AIR VEL(EFFECTIVE) IN JET,WITHOUT SPRAY,M/S                   00219000
C VISKIN=LOCAL AIR KINETIC VISCOSITY,M2/S                               00220000
C VLIQ=INITIAL LIQ. VOL. FRACTION IN DROPS                              00221000
C VRTSQ(J)=SQUARED REL.VEL. DUE TO TURBULENCE,M2/S2                     00222000
C VO=VEL. OF ATOMISING AIR EMERGING FROM NOZZLE,M/S                     00223000
C W(J)=SQUARED VELOCITY OF DRIPLET,M2/S2                                00224000
C WAGRAD=LOCAL AIR SQUARED VEL. GRADIENT                                00225000
C WB=ADIABATIC-SATURATION TEMPERATURE OF EVAPORATING SOLUTION,K         00226000
C WBULB=SUBROUTINE CALCULATING ADIABATIC SATURATION TEMPERATURE &       00227000
C HUMIDITY,OR SATURATION HUMIDITY AT A GIVEN TEMPERATURE                00228000
C FOR A GIVEN EVAPORATING SOLUTION                                      00229000
C WLCRIT=WET BASIS MOISTURE CONTENT AT SOLIDIFICATION                   00230000
C WLIQ=1-WSOL=INITIAL LIQ. MASS FRACTON                                 00231000
C WOLD(J)=OLD W(J),M2/S2                                                00232000
C WRAD(I)=RADIATION 'LEAVING FLUX DENSITY' AT PT I,DEFINED BY HOTTEL ,  00233000
C ALSO CALLED RADIOSITY,W/M3 STERADIAN                                  00234000
C WSOL=MASS FRACTION SOLID IN INITIAL FEED,KG/KG                        00235000
C X(I)=DISTANCE FROM NOZZLE,M                                           00236000
C XEND=TOTAL LENGTH CONSIDERED,M                                        00237000
C XJET=LENGTH OF JET ZONE(UP TO TRANSITION),M                           00238000
C XTRA=LENGTH UP TO END OF TRANSITION ZONE,M                            00239000
C Y(I)=EFFECTIVE HUMIDITY OF AIR IN JET,KG/KG                           00240000
C YEXT=HUMIDITY OF EXTERNAL AIR FLOW,KG/KG                              00241000
C YRISE=RISE IN AIR HUMIDITY DUE TO EVAPORATION,KG/KG                   00242000
C YSAT=ADIABATIC SATURATION HUMIDITY OF WATER,KG/KG DRY AIR             00243000
C YSURF=SURFACE HUMIDITY OF DROPLETS,KG/KG DRY AIR                      00244000
C YO=ATOMISING AIR HUMIDITY DRY BASIX,KG/KG                             00245000
C YO WILL BE RECALC TO GIVE HYGROTHERMAL EQM WITH FEED                  00246000
C                                                                       00247000
C                                                                       00248000
C ***********************************************************************00249000
C                                                                       00250000
C                                                                       00251000
C                                                                       00252000
C                                                                       00253000
      LOGICAL COND,COND1                                                00254000
      DIMENSION VAIR(1001),D32(1001),E(1001),D(20),W(20),V(20),DVOL(20),00255000
     $AMSIZE(20),ESIZE(20),DN(20),DO(20),ESOLD(20),WOLD(20),DEN(20),    00256000
     $T(1001),TS(20),DCR(20),VRTSQ(20),RCP1(20),CSJ(20),                00257000
     $WRAD(1001),DSOLD(20),DENOLD(20),TDR(20),RTI(20),RATE(20)          00258000
      COMMON/INIT/VINI(1001),YINIT(1001),G(1001),TINIT(1001),X(1001),   00259000
     $RJET,VO,GO,TO,YO,FO,VEXT,GEXT,TEXT,YEXT,NP1,NP2,NPT,NP3           00260000
     $,TUIN(1001),TUSC(1001),TUINO,TUINI,TUSCO,TUSCI,TLOSS,DENSF,HAJ    00261000
      COMMON /VELEP/ DENSLO,WSOL,WLIQ,VLIQ,COEFF2,HTLAT,DENLIQ,ECRIT,   00262000
     $DCRIT,TAIR, VA ,DENS,VISKIN,THCOND,TWB,DENSL,DINIT,DIA,RE,VELD ,  00263000
     $CDRESQ,WAGRAD,SQVRT,CRAD,RADIOS,QRCP1,CSS                         00264000
C                                                                       00265000
C                                                                       00266000
C                                                                       00267000
C                                                                       00268000
C                                                                       00269000
C                                                                       00270000
C                                                                       00271000
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C                                                                       00272000
C                                                                       00273000
C                                                                       00274000
C ***********************************************************************00275000
C  INPUT INITIAL CONDITIONS                                             00276000
C  CARD 1:LAST 2 DATA OPTIONAL                                          00277000
C  CARD 3:FOR PNEUMATIC NOZZLE ONLY                                     00278000
C  CARD 5:LAST 4 DATA OPTIONAL(FOR CALC EFFECT OF TURBULENCE ONLY)      00279000
C  A FUNCTION FCURVE(AMOIST,D,RATE) MUST BE SUPPLIED TO CALC. RELATIVE  00280000
C  DRYING RATE                                                          00281000
C  SUBR. SPRAY MUST SUPPLY INITIAL SIZES DO(J),NUMBER OF DROPLETS IN    00282000
C  EACH SIZE RANGE DN(J)(NON NORMALISED),NUMBER OF SIZE RANGES          00283000
C                                                                       00284000
C                                                                       00285000
1       FORMAT(8F10.0)                                                  00286000
        READ(5,1)XJET,XTRA,DX1,XEND,DX2,PRINT1,PRINT2                   00287000
        READ(5,1)ANOZ,RJET,VELOUT,HAJ                                   00288000
        READ(5,1)VO,GO,TO,YO                                            00289000
        READ(5,1)FO,WSOL,DENSOL,DENLIQ,HTLAT,WLCRIT,CF,TF               00290000
        READ(5,1)RS                                                     00291000
        READ(5,1)GEXT,TEXT,YEXT,VEXT,TLOSS                              00292000
        READ(5,1)TUINO,TUIN1,TUSCO,TUSC1                                00293000
        READ(5,1)RADCAL,DHY,EXC,EMIS,EMIW,TWA                           00294000
        IF(RADCAL.GT.0.)READ(5,1)(WRAD(I),I=1,1001)                     00295000
        CALL SPRAY(DO,DN,NSIZE)                                         00296000
C                                                                       00297000
C                                                                       00298000
C  END OF DATA INITIALISATION                                           00299000
C ***********************************************************************00300000
C                                                                       00301000
C                                                                       00302000
C                                                                       00303000
C                                                                       00304000
C                                                                       00305000
C                                                                       00306000
C                                                                       00307000
C                                                                       00308000
C                                                                       00309000
C                                                                       00310000
        PRINT 2    ,XJET,XTRA,XEND,DX1,DX2                              00311000
        PRINT 12   ,ANOZ,HAJ                                           00312000
        PRINT 22,RJET,VO,GO,TO,YO,FO,WSOL,DENSOL,DENLIQ,HTLAT,          00313000
       $WLCRIT,CF,TF,GEXT,TEXT,YEXT,VEXT,TLOSS                          00314000
        PRINT 32  ,TUINO,TUIN1,TUSCO,TUSC1,DHY,EXC,EMIS,EMIW,TWA,       00315000
       $RADCAL                                                          00316000
        IF(PRINT1.EQ.0)PRINT1=DX1                                       00317000
        IF(PRINT2.EQ.0)PRINT2=DX2                                       00318000
        NP1=XTRA/DX1+1.1                                                00319000
        IF(NP1.GT.1001)NP1=1001                                         00320000
        NP2=(XEND-XTRA)/DX2+0.1                                         00321000
        IF(NP2.GT.1001-NP1)NP2=1001-NP1                                 00322000
        NPT=NP1+NP2                                                     00323000
        NP3=XJET/DX1+1.1                                                00324000
        IF(NP3.GT.NP1)NP3=NP1                                           00325000
        WLIQ=1.-WSOL                                                    00326000
        VLIQ=DENSOL*WLIQ                                                00327000
        VLIQ=VLIQ/(VLIQ+DENLIQ*WSOL)                                    00328000
        ECRIT=(1.-WLCRIT/WLIQ)/(1.-WLCRIT)                              00329000
        DENSLO=WSOL/DENSOL+WLIQ/DENLIQ                                  00330000
        DENSLO=1./DENSLO                                                00331000
        DENSF=DENSLO                                                    00332000
        COEFF2=6./HTLAT/WLIQ/DENSLO                                     00333000
        CPGAS=1.E3                                                      00334000
        HRATIO=FO*WLIQ*HTLAT/CPGAS                                      00335000
        HCW=HTLAT*WLIQ/CF                                               00336000
        IF(ANOZ.GT.0.)GOTO 10                                           00337000
        VO=VELOUT                                                       00338000
        GO=0.                                                           00339000
        TO=TF                                                           00340000
10      CONTINUE                                                        00341000
C  CALC VOLUME FRACTIONS IN SPRAY ,CRIT.DIAS AND INITIAL SAUTER DIA.    00342000
        SHRINK=(1.-ECRIT*VLIQ)**(1./3.)                                 00343000
        SUM2=0                                                          00344000
        SUM3=0                                                          00345000
        DO 20   J=1,NSIZE                                              00346000
        DVOL(J)=DN(J)*DO(J)**3                                          00347000
        VOL=VOL+DVOL(J)                                                 00348000
        DD=DO(J)*DO(J)*DN(J)                                            00349000
        DDD=DD*DO(J)                                                    00350000
        SUM2=SUM2+DD                                                    00351000
        SUM3=SUM3+DDD                                                   00352000
        DCR(J)=DO(J)*SHRINK                                             00353000
20      CONTINUE                                                        00354000
        D32(1)=SUM3/SUM2                                                00355000
        DO 30   J=1,NSIZE                                               00356000
30      DVOL(J)=DVOL(J)/VOL                                             00357000
        IF(NP1.EQ.1)GOTO 50                                             00358000
        DO 40   I=2,NP1                                                 00359000
40      X(I)=X(I-1)+DX1                                                 00360000
        IF(NP2.EQ.0)GOTO 70                                             00361000
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50    DO 60  I=NP1+1,NPT                                                    00362000
60    X(I)=X(I-1)+DX2                                                       00363000
70    CONTINUE                                                              00364000
      PRINT 42, RS                                                          00365000
      PRINT 52',WSOL,VLIQ,ECRIT,DENSLO,COEFF2,VELOUT,SHRINK                 00366000
      DENSL=DENSLO                                                          00367000
C                                                                           00368000
C ASSUMING HYGROTHERMAL EQM AT NOZZLE EXIT,RECALC AIR&FEED TEMPERATURE      00369000
C & HUMIDITY,ETC...                                                         00370000
      IF(NP1.EQ.1)GOTO 90                                                   00371000
      SHA=GO*((1.-YO)*1.E3+YO*1.89E3)                                       00372000
      SHF=FO*CF                                                             00373000
      HTT=SHF*TF+SHA*TO                                                     00374000
      TO=HTT/(SHA+SHF)                                                      00375000
      K9=HTLAT*GO/(SHA+SHF)                                                 00376000
      TW=TO                                                                 00377000
      DO 75  ITER=1,20                                                      00378000
      CALL WBULB(0.,0.,TW,YSURF,DER,CS,RS,1.,-1)                            00379000
      DERIV=K9*DER+1.                                                       00380000
      FTN=K9*(YSURF-YO)+TW-TO                                               00381000
      DTW=-FTN/DERIV                                                        00382000
      IF(ABS(DTW).LE.0.05)GOTO 80                                           00383000
      TW=TW+DTW                                                             00384000
75    CONTINUE                                                              00385000
      PRINT 62 ,DTW                                                         00386000
80    CONTINUE                                                              00387000
      TO=TW                                                                 00388000
      TF=TW                                                                 00389000
      WB=TW                                                                 00390000
      TSAVE=TW                                                              00391000
      EAV=(YSURF-YO)*GO/FO/WLIQ                                             00392000
      EOLD=EAV                                                              00393000
      E(1)=EAV                                                              00394000
      YO=YSURF                                                              00395000
      DENSL=DENSLO*(1.-WLIQ*E(1))/(1.-VLIQ*E(1))                            00396000
90    CONTINUE                                                              00397000
C CALCULATE INITIAL PROFILE OF JET(VEL.,TEMP.,ENTRAINMENT,HUMIDITY..)       00398000
C                                                                           00399000
      CALL PROFI1                                                           00400000
      CALL PROFIL(ANOZ)                                                     00401000
C                                                                           00402000
C SET INITIAL VALUES OF DROP DIAS,VEL.,KIN.ENERGIES,SURFACE TEMP...         00403000
      EAV=E(1)                                                              00404000
      CRAD=0.                                                               00405000
C  (ASSUME NO RADIATION EFFECT IN JET&TRANSITION ZONES)                     00406000
      RTIME=0.                                                              00407000
      AM=VELOUT                                                             00408000
      AMOLD=VELOUT                                                          00409000
      AMAV=VELOUT                                                           00410000
      IF(NP1.NE.1)GOTO 100                                                  00411000
      CALL WBULB(TINIT(1),YINIT(1),WB,YSAT,DER,CS,RS,TINIT(1),1)            00412000
      WBDEP=TINIT(1)-WB                                                     00413000
      AMOIST=WLIQ*(1.-E(1))/(1.-WLIQ*E(1))                                  00414000
      FAC=FCURVE(AMOIST,D32(1),0.,WLIQ)                                     00415000
      YSURF=YINIT(1)+(YSAT-YINIT(1))*FAC                                    00416000
      TSAVE=TINIT(1)-WBDEP*FAC                                              00417000
100   CONTINUE                                                              00418000
      CSS=YSURF*1.89E3+(1.-YSURF)*1.E3                                      00419000
      T(1)=TINIT(1)                                                         00420000
      T(2)=TINIT(2)                                                         00421000
      VAIR(1)=VINI(1)                                                       00422000
      ECOMP=1.-E(1)                                                         00423000
      SHRO=(1.-VLIQ*E(1))**(1./3.)                                          00424000
      EOO=0.                                                                00425000
      DO 110 J=1,NSIZE                                                      00426000
      RATE(J)=0.                                                            00427000
      RTI(J)=0.                                                             00428000
      TDR(J)=TF                                                             00429000
      D(J)=DO(J)**SHRO                                                      00430000
      DSOLD(J)=D(J)                                                         00431000
      ESOLD(J)=E(1)                                                         00432000
      ESIZE(J)=E(1)                                                         00433000
      V(J)=VELOUT                                                           00434000
      W(J)=VELOUT*VELOUT                                                    00435000
      WOLD(J)=W(J)                                                          00436000
      TS(J)=TSAVE                                                           00437000
      DEN(J)=DENSL                                                          00438000
      DENOLD(J)=DEN(J)                                                      00439000
      RCP1(J)=1.                                                            00440000
      CSJ(J)=CSS                                                            00441000
110   CONTINUE                                                              00442000
      IF(NP1.NE.1)PRINT 102                                                 00443000
      IF(NP1.NE.1)PRINT 72                                                  00444000
      IF(NP1.NE.1)PRINT 192,X(1),T(1),TSAVE,1.-E(1),VAIR(1),G(1),D32(1)     00445000
C                                                                           00446000
C START TO CALC. EVAPORATION PROFILE                                        00447000
C                                                                           00448000
C AT EACH POSITION &&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&00449000
C                                                                           00450000
      DX=DX1                                                                00451000
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      NPRINT=PRINT1/DX1+.1                                                    00452000
      DO 340 I=2,NPT                                                          00453000
C                                                                             00454000
C CALC AIR PROERTIES IN FILM AROUND DROPLETS                                  00455000
      TAV=(T(I-1)+TSAVE)/2                                                    00456000
      DENS =  1.293*273/TAV                                                   00457000
      VISKIN =  1.488E-6*TAV**1.5/(TAV+122.1*EXP(-11.5/TAV))/DENS             00458000
      THCOND =  2.646E-3*TAV**1.5/(TAV+245.*EXP(-27.64/TAV))                  00459000
      VAIR(I)=VINI(I)*T(I)/TINIT(I)                                           00460000
C                                                                             00461000
      IF(I.NE.NP1+1)GOTO 170                                                  00462000
C                                                                             00463000
C RESET PARAMETERS ,INITIAL CONDITNS & PRINT HEADINGS FOR MAIN ZONE           00464000
C                                                                             00465000
C                                                                             00466000
C                                                                             00467000
C                                                                             00468000
      IF(NP1.NE.1)PRINT 82                                                    00469000
C                                                                             00470000
C CALC RADIATION PARAMETERS                                                   00471000
      IF(RADCAL.GE.0.)GOTO 140                                                00472000
      RADIOS=TWA**4.                                                          00473000
      SH=1.                                                                   00474000
      IF(EXC.EQ.0.)GOTO 120                                                   00475000
      DHYEXC=DHY*EXC                                                          00476000
      SH=1./DHYEXC/EMIS                                                       00477000
      IF(DHYEXC.GT.10.)GOTO 120                                               00478000
      BE=-ALOG(8./9./DHYEXC**2.*(1.-(1.+1.5*DHYEXC)*EXP(-1.5*DHYEXC)))        00479000
      EBE=EXP(-BE)                                                            00480000
      EBE2=EXP(-BE/2.)                                                        00481000
      FCL=EMIS*(1.-EBE)/(1.-(1.-EMIS)*(1.-EBE2))                              00482000
      SH=1./EMIS/DHYEXC/(1./FCL+1./EMIW-1.)                                   00483000
120   CONTINUE                                                                00484000
      CRAD =5.67E-8*SH*EMIS                                                   00485000
140   CONTINUE                                                                00486000
C                                                                             00487000
      PRINT 112                                                               00488000
      IF(RADCAL.LT.0.)PRINT 242 ,FCL,SH,CRAD                                  00489000
      PRINT 72                                                                00490000
      IF(NP1.EQ.1)PRINT 192,X(1),T(1),TSAVE,1.-E(1),VAIR(1),G(1),D32(1)       00491000
      DX=DX2                                                                  00492000
      NPRINT=PRINT2/DX2+.1                                                    00493000
      IF(XJET.NE.XTRA)GOTO 150                                                00494000
      VINI(NP1)=VINI(NP1+1)                                                   00495000
      YINIT(NP1)=YINIT(NP1+1)                                                 00496000
      G(NP1)=G(NP1+1)                                                         00497000
      TINIT(NP1)=TINIT(NP1+1)                                                 00498000
      T(NP1)=TINIT(NP1)-E00*HRATIO/G(NP1)                                     00499000
      VAIR(NP1)=VINI(NP1)*T(NP1)/TINIT(NP1)                                   00500000
      YAIR  =  YINIT(NP1)+E(NP1)*FO*WLIQ/G(NP1)                               00501000
150   CONTINUE                                                                00502000
      DO 160  J=1,NSIZE                                                       00503000
      IF(D(J).LE.0.)GOTO 160                                                  00504000
C AT START OF MAIN ZONE DROPLETS ARE APPROSLY AT TERMINAL VEL WRT AIR         00505000
C CALC. TERMINAL VELOCITIES FROM SMITH                                        00506000
      CDRESQ=1.33*DEN(J)*9.8*D(J)**3/DENS/VISKIN/VISKIN                       00507000
      IF((CDRESQ.GT.10.).AND.(XJET.NE.XTRA))GOTO 160                          00508000
      CDRT=574./CDRESQ+32./CDRESQ**.39+1./(1.8+758/CDRESQ**.36)               00509000
      IF(CDRESQ.LE.10.)CDRT=576./CDRESQ                                       00510000
      VTERM=SQRT(4.*D(J)*DEN(J)*9.8/3./DENS/CDRT)                             00511000
      V(J)=VAIR(NP1)+VTERM                                                    00512000
      W(J)=V(J)*V(J)                                                          00513000
      WOLD(J)=W(J)                                                            00514000
160   CONTINUE                                                                00515000
C FINISH RESETTING FOR MAIN ZONE                                              00516000
170   CONTINUE                                                                00517000
C                                                                             00518000
      IF(G(I).NE.0.)TFINIT=E00*HRATIO/G(I)                                    00519000
      TFM=TINIT(I)-TFINIT-WB                                                  00520000
      IF(TFM.LT.0.)TFM=0.                                                     00521000
      EMAX=E(I-1)+TFM*G(I)/HRATIO                                             00522000
      AMMAX=(G(I)*VINI(I)+FO*VELOUT)/(G(I)+FO)                                00523000
C     START ITERATING AT I-TH PT  ---------------------------------------     00524000
C                                                                             00525000
      DO 240 ITER=1,20                                                        00526000
      COND=(ITER.GT.14).OR.(EMAX.LE.E(I-1))                                   00527000
      IF(RADCAL.GT.0.)RADIOS=WRAD(I)/5.67E-8                                  00528000
C                                                                             00529000
C CALC SQUARED REL VEL DUE TO TURBULENCE                                      00530000
      DO 180  J=1,NSIZE                                                       00531000
      IF(DSOLD(J).LE.0.)GOTO 180                                              00532000
      VRELAB=ABS(V(J)-VAIR(I-1))                                              00533000
      REY=VRELAB*DSOLD(J)/VISKIN                                              00534000
      CDR=DRAG(REY)                                                           00535000
      ATP=3.*CDR*DENS*VRELAB/4./DSOLD(J)/DENOLD(J)                            00536000
      VRTSQ(J)=TUIN(I-1)/(1.+ATP*TUSC(I-1))                                   00537000
180   CONTINUE                                                                00538000
C                                                                             00539000
C     RECALC. AIR T, PROP & VEL PROFILE                                       00540000
      IF(I.LE.NP1.AND.ANOZ.GT.0.)VAIR(I)=VINI(I)-(AMAV-VELOUT)*FO/G(I)        00541000
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      IF(G(I).NE.0.)TFALL=(EAV-E(I-1)+E00)*HRATIO/G(I)                  00542000
      T(I)=TINIT(I)-TFALL                                              00543000
      IF(T(I).LT.TSAVE )T(I)=TSAVE                                     00544000
      T1=T(I)                                                          00545000
      E(I)=0.                                                          00546000
      AM=0                                                             00547000
C                                                                      00548000
C     CALC. EVAPN & MEAN VEL. OF EACH SIZE RANGE <<<<<<<<<<<<<<<<<<<<<<00549000
      DO 220 J=1,NSIZE                                                 00550000
      IF(DSOLD(J).GT.0.)GOTO 190                                       00551000
      ESIZE(J)=1.                                                      00552000
      AMSIZE(J) = VAIR(I)                                              00553000
      GOTO 210                                                         00554000
190   CONTINUE                                                         00555000
C                                                                      00556000
C SOLVE DIFF.EQNS. WITH RUNGE-KUTTA METHOD ++++++++++++++++++++++++++++00557000
C SET UP THE PARAMETERS OF THE D.E.                                    00558000
C                                                                      00559000
      CSS=CSJ(J)                                                       00560000
      SQVRT=VRTSQ(J)                                                   00561000
      TWB=TS(J)                                                        00562000
      DCRIT=DCR(J)                                                     00563000
      DINIT=DO(J)                                                      00564000
      VA=VAIR(I-1)                                                     00565000
      TAIR=T(I-1)                                                      00566000
      CDRESQ=100.                                                      00567000
      IF((I.LE.NP1).AND.(ANOZ.GT.0.))GOTO 200                          00568000
      CDRESQ=1.333*DEN(J)*9.8*D(J)**3/DENS/VISKIN/VISKIN               00569000
      IF(CDRESQ.GT.0.1)GOTO 200                                        00570000
C FOR SMALL PTCLES IN MAIN ZONE ASSUME COMPLETE ENTRAINMENT            00571000
      V1=VAIR(I)                                                       00572000
      V2=VAIR(I-1)                                                     00573000
      WAGRAD=(V1*V1-V2*V2)/DX                                          00574000
      W(J)=V2*V2                                                       00575000
200   CONTINUE                                                         00576000
C RUNGE-KUTTA 4-TH ORDER .                                             00577000
      AK1=DX*F1(W(J),ESIZE(J))                                         00578000
      AL1=DX*F2(W(J),ESIZE(J))                                         00579000
      IF(COND)AL1=0.                                                   00580000
      VA=(VAIR(I-1)+VAIR(I))/2                                         00581000
      TAIR=(T(I-1)+T(I))/2                                             00582000
      AK2=DX*F1(W(J)+AK1/2,ESIZE(J)+AL1/2)                             00583000
      AL2=DX*F2(W(J)+AK1/2,ESIZE(J)+AL1/2)                             00584000
      IF(COND)AL2=0.                                                   00585000
      AK3=DX*F1(W(J)+AK2/2,ESIZE(J)+AL2/2)                             00586000
      AL3=DX*F2(W(J)+AK2/2,ESIZE(J)+AL2/2)                             00587000
      IF(COND)AL3=0.                                                   00588000
      VA=VAIR(I) .                                                     00589000
      TAIR=T(I)                                                        00590000
      AK4=DX*F1(W(J)+AK3,ESIZE(J)+AL3)                                 00591000
      AL4=DX*F2(W(J)+AK3,ESIZE(J)+AL3)                                 00592000
      IF(COND)AL4=0.                                                   00593000
      W(J)=W(J)+(AK1+2*AK2+2*AK3+AK4)/6                                00594000
      ESIZE(J)=ESIZE(J)+(AL1+2*AL2+2*AL3+AL4)/6                        00595000
C                                                                      00596000
C END OF RUNGEKUTTA CALCULATION ++++++++++++++++++++++++++++++++++++++00597000
C                                                                      00598000
C IF ITERATION DOESNT CONVERGE SET ESIZE(J)=0.                         00599000
C                                                                      00600000
      IF(ESIZE(J).GT.1.)ESIZE(J)=1.                                    00601000
      IF(W(J).LE.0.)W(J)=VAIR(I)*VAIR(I)                               00602000
      V(J)=SQRT(W(J))                                                  00603000
      RCP1(J)=QRCP1                                                    00604000
      IF(ESIZE(J) .LT.ECRIT)D(J)=DINIT*(1.-VLIQ*ESIZE(J))**(1./3.)     00605000
      IF(ESIZE(J).GE.ECRIT)D(J)=DCR(J)                                 00606000
      EE=ESIZE(J)*WLIQ                                                 00607000
C EE=RATIO MASS EVAPORATED/MAS(SOL+LIQ) REMAINING                      00608000
      AMSIZE(J) = V(J)*(1.-EE)+VAIR(I)*EE                              00609000
210   CONTINUE                                                         00610000
C                                                                      00611000
C TOTAL EVAPORATION AND SPRAY MOMENTUM/UNIT MASS FEED                  00612000
      E(I)=E(I)+ESIZE(J)*DVOL(J)                                       00613000
      AM=AM+AMSIZE(J)*DVOL(J)                                          00614000
220   CONTINUE                                                         00615000
C                                                                      00616000
C FINISHED CONSIDERING J-TH SIZE RANGE  <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<00617000
C                                                                      00618000
C WEIGHTING FACTORS TO ACCELERATE CONVERGENCE                          00619000
      DENOM1=AMMAX+AM-AMOLD-AMAV                                       00620000
      IF(DENOM1.NE.0.)AMAV=(AM*AMMAX-AMAV*AMOLD)/DENOM1                00621000
      DENOM=EMAX+E(I)-E(I-1)-EAV                                       00622000
      IF(DENOM.NE.0.)EAV=(E(I)*EMAX-EAV*E(I-1))/DENOM                  00623000
      IF(COND)EAV=E(I)                                                 00624000
C                                                                      00625000
C TESTING FOR CONVERGENCE BY CONSIDERING THE CHANGE IN EVAPORN&MOM.    00626000
      DEV=EAV-E(I-1)                                                   00627000
      TEST=E(I)-EAV                                                    00628000
      TEST1=ABS(TEST)                                                  00629000
      IF(DEV.EQ.0.)DEV=1.E-10                                          00630000
      TEST=TEST1/DEV                                                   00631000
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      DAM=0.                                                            00632000
      IF((ANOZ.GT.0.).AND.(I.LE.NP3))DAM=ABS((AM-AMAV)/AM)              00633000
      COND1=(TEST.LE.0.05).OR.(TEST1.LT.1.E-5)                          00634000
      COND1=COND1.AND.(E(I).LE.EMAX)                                    00635000
      COND1=COND1.AND.(DAM.LE.0.05)                                     00636000
      COND1=COND1.OR.(EMAX.LE.E(I-1))                                   00637000
      IF(COND1)GOTO 250                                                 00638000
C                                                                       00639000
C RESET EVAPORATNS & VELOCITITIES BEFORE REPEATING THE CALCN.           00640000
      IF(ITER.EQ.20) GO TO 240                                          00641000
      DO 230  J=1,NSIZE                                                 00642000
      ESIZE(J)=ESOLD(J)                                                 00643000
      W(J)=WOLD(J)                                                      00644000
      D(J)=DSOLD(J)                                                     00645000
230   CONTINUE                                                          00646000
240   CONTINUE                                                          00647000
C                                                                       00648000
C END OF ITERATIONS AT I-TH POINT ------------------------------------00649000
C                                                                       00650000
      PRINT 122,X(I),TEST,E(I),DAM,AM,TSAVE,T(I)                        00651000
250   CONTINUE                                                          00652000
      IF(E(I).GT.0.9999)GOTO 350                                        00653000
C                                                                       00654000
C CORRECT FOR INFLUENCE OF DROPLET OVERHEAT AS WELL AS SET UPPER        00655000
C LIMIT ON EVAPORATION                                                  00656000
      DEI=E(I)-E(I-1)                                                   00657000
      EOO=EOO+DEI                                                       00658000
      SET=1.                                                            00659000
      IF((E(I).EQ.E(I-1)).OR.(EMAX.EQ.E(I)))GOTO 280                    00660000
      SEMAX=(EMAX-E(I-1))/(E(I)-E(I-1))                                 00661000
      E(I)=0.                                                           00662000
      DO 270  J=1,NSIZE                                                 00663000
      SE=1.                                                             00664000
      IF(TDR(J).LT.TS(J))GOTO 260                                       00665000
      CALL WBULB(0.,0.,TDR(J),YDR,DUM1,CSDUM,RS,0.,-1)                  00666000
      IF(YSAT.NE.YAIR)SE=(YDR-YAIR)/(YSAT-YAIR)                         00667000
      IF(SE.GT.SEMAX)SE=SEMAX                                           00668000
      IF(SE.LT.1.)SE=1.                                                 00669000
      DESIZE=ESIZE(J)-ESOLD(J)                                          00670000
      SEMAX1=SEMAX                                                      00671000
      IF(DESIZE.GT.0.)SEMAX1=1.+(TDR(J)-TS(J)+1.)*(1.-WLIQ*ESIZE(J))/   00672000
     $HCW/DESIZE                                                        00673000
      IF(SE.GT.SEMAX1)SE=SEMAX1                                         00674000
      ESIZE(J)=ESOLD(J)+DESIZE*SE                                       00675000
260   CONTINUE                                                          00676000
      IF(ESIZE(J).GT.1.)ESIZE(J)=1.                                     00677000
      IF(ESIZE(J).LT.ECRIT)D(J)=DO(J)*(1.-VLIQ*ESIZE(J))**(1./3.)       00678000
      IF(ESIZE(J).GE.ECRIT)D(J)=DCR(J)                                  00679000
      ANUM=1.-WLIQ*ESIZE(J)                                             00680000
      IF((ESIZE(J).LT.ECRIT).AND.(VLIQ*ESIZE(J).NE.1.))                 00681000
     $DEN(J)=DENSLO*ANUM/(1.-VLIQ*ESIZE(J))                             00682000
      IF((ESIZE(J).GE.ECRIT).AND.(VLIQ*ECRIT.NE.1.))                    00683000
     $DEN(J)=DENSLO*ANUM/(1.-VLIQ*ECRIT)                                00684000
      E(I)=E(I)+ESIZE(J)*DVOL(J)                                        00685000
      IF(T(I).EQ.TS(J))GOTO 270                                         00686000
      IF(WLIQ*ESIZE(J).EQ.1.)GOTO 270                                   00687000
      SEH=(T(I)-TDR(J))/(T(I)-TS(J))                                    00688000
      DTDR=HCW/(1-WLIQ*ESIZE(J))*(SE-SEH)*(ESIZE(J)-ESOLD(J))           00689000
      TDR(J)=TDR(J)-DTDR                                                00690000
270   CONTINUE                                                          00691000
      SET=(E(I)-E(I-1))/DEI                                             00692000
280   CONTINUE                                                          00693000
      VDROPS=(AM-VAIR(I)*E(I)*WLIQ)/(1.-E(I)*WLIQ)                      00694000
      RTIME=RTIME+DX/VDROPS                                             00695000
C CALC. MEAN DIAMETER                                                   00696000
      SUM3=0                                                            00697000
      SUM2=0                                                            00698000
      DRTIME=0.                                                         00699000
      DO 290 J=1,NSIZE                                                  00700000
      IF(ESIZE(J).GT.0.9999)JEV=J                                       00701000
      DRTI=DX/V(J)                                                      00702000
      RTI(J)=RTI(J)+DRTI                                                00703000
      RATE(J)=ESIZE(J)/RTI(J)                                           00704000
      DD=D(J)*D(J)*DN(J)                                                00705000
      DDD=DD*D(J)                                                       00706000
      SUM2=SUM2+DD                                                      00707000
      SUM3=SUM3+DDD                                                     00708000
290   CONTINUE                                                          00709000
      D32(I)=SUM3/SUM2                                                  00710000
C                                                                       00711000
C SET UP CONDITIONS FOR NEXT POSITION                                   00712000
      EAV=E(I)                                                          00713000
      AMOLD=AM                                                          00714000
      AMMAX=AM                                                          00715000
      YRISE=0.                                                          00716000
      TFALL=0.                                                          00717000
      IF(G(I).EQ.0.)GOTO 300                                            00718000
      EVAP=E(I)*FO*WLIQ                                                 00719000
      YRISE=EVAP/G(I)                                                   00720000
      IF(G(I).NE.0.)TFALL=EOO*HRATIO/G(I)                               00721000
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300   CONTINUE                                                          00722000
      YAIR=YINIT(I)+YRISE                                               00723000
      T(I)=TINIT(I)-TFALL                                               00724000
      IF(I.LE.NP1.AND.ANOZ.GT.0.)VAIR(I)=VINI(I)-(AM-VELOUT)*FO/G(I)    00725000
C CALC. DROPLET MOISTURE,WET BASIS,IN ORDER TO CALC SURF. TEMP.& DENSITY00726000
      WBO=WB                                                            00727000
      CALL WBULB(T(I),YAIR,WB,YSAT,DER,CS,KS,WBO,1)                     00728000
      WBDEP=T(I)-WB                                                     00729000
      DO 310  J=1,NSIZE                                                 00730000
      IF(D(J).LE.0.)GOTO 310                                            00731000
      AMOIST=(1.-ESIZE(J))*WLIQ                                         00732000
      AMOIST=AMOIST/(AMOIST+WSOL)                                       00733000
      FAC=FCURVE(AMOIST,D(J),RATE(J),WLIQ)                              00734000
      YSURF=YINIT(I)+(YSAT-YINIT(I))*FAC                                00735000
      CSJ(J)=YSURF*1.89E3+(1.-YSURF)*1.E3                               00736000
      TS(J)=T(I)-WBDEP*FAC                                              00737000
310   CONTINUE                                                          00738000
C                                                                       00739000
      TSAVE=0                                                           00740000
      ECOMP=1.-E(I)                                                     00741000
      DO 320 J=1,NSIZE                                                  00742000
      TSAVE=TSAVE+TS(J)*(1.-ESIZE(J))*DVOL(J)/ECOMP                     00743000
      ESOLD(J)=ESIZE(J)                                                 00744000
      WOLD(J)=W(J)                                                      00745000
      DSOLD(J)=D(J)                                                     00746000
      DENOLD(J)=DEN(J)                                                  00747000
320   CONTINUE                                                          00748000
      IPRINT=MOD(I-1,NPRINT)*(I-NP1)*(I-NPT)                            00749000
      FE=1.-E(I)                                                        00750000
      IF(IPRINT.EQ.0)PRINT 192,X(I),T(I),TSAVE,FE,VAIR(I),G(I),D32(I),  00751000
     $VDROPS,RTIME,YAIR,SET,JEV,ITER                                    00752000
      IPR1=MOD(I-1,10*NPRINT)                                           00753000
      IF(IPR1.NE.0)GOTO 330                                             00754000
      PRINT 132                                                         00755000
      PRINT 142 ,(( TS(J)),J=1,NSIZE)                                   00756000
      PRINT 152 ,((TDR(J)),J=1,NSIZE)                                   00757000
      PRINT 162,((1.-ESIZE(J)),J=1,NSIZE)                               00758000
      PRINT 172 ,((V(J)),J=1,NSIZE)                                     00759000
      PRINT 182 ,((RTI(J)),J=1,NSIZE)                                   00760000
      PRINT 132                                                         00761000
330   CONTINUE                                                          00762000
      IF(I.EQ.NPT) GO TO 340                                            00763000
      E(I+1)=E(I)                                                       00764000
      EAV=E(I)                                                          00765000
      AMOLD=AM                                                          00766000
      T(I+1)=TINIT(I+1)                                                 00767000
      IF(G(I+1).NE.0.)T(I+1)=TINIT(I+1)-E00* HRATIO/G(I+1)              00768000
C FINISHED CALCULATIONS FOR THIS POSITION- &&&&&&&&&&&&&&&&&&&&&&&&&&&&00769000
340   CONTINUE                                                          00770000
C                                                                       00771000
C                                                                       00772000
350   CONTINUE                                                          00773000
      IF(NP2.EQ.0)PRINT 82                                              00774000
      IF(NP2.NE.0)PRINT 202                                             00775000
      PRINT 212                                                         00776000
      CALL PLOT1(E,NPT,0.,DX,0.,1.,5)                                   00777000
      PRINT 222                                                         00778000
      CALL PLOT1(T,NPT,0.,DX,0.,0.,5)                                   00779000
      PRINT 232                                                         00780000
      CALL PLOT1(D32,NPT,0.,DX,0.,0.,5)                                 00781000
      STOP                                                              00782000
2     FORMAT('OXTRANS=',E10.3/' XTRA=',E10.3/' XEND=',E10.3/            00783000
     $' DX1=',E10.3/' DX2=',E10.3)                                      00784000
12    FORMAT('OANOZ=',E10.3/' HAJ=',E10.3 )                             00785000
22     FORMAT('ORJET=',E10.3/'OVO=',E10.3/' GO=',E10.3/                 00786000
     1' TO=',E10.3/' YO=',E10.3/' FO=',E10.3//                          00787000
     2' WSOL=',E10.3/' DENSOL=',E10.3/' DENLIQ=',E10.3/' HTLAT=',E10.3/ 00788000
     3' WLCRIT=',E10.3/' CF=',E10.3/' TF=',E10.3//' GEXT=',E10.3/       00789000
     4' TEXT=',E10.3/' YEXT=',E10.3/' VEXT=',E10.3/                     00790000
     5' TLOSS=',E10.3//)                                                00791000
32    FORMAT(' TUINO=',E10.3/' TUIN1=',E10.3/' TUSCO=',E10.3/' TUSC1=', 00792000
     $E10.3///' DHY=',E10.3/' EXC=',E10.3/' EMIS=',E10.3/' EMIW=',E10.3/00793000
     $' TWA=',E10.3/' RADCAL=',E10.3///)                                00794000
42    FORMAT(' RS=',E10.3)                                              00795000
52    FORMAT(' WSOL=',E10.3/' VLIQ=',E10.3/' ECRIT=',E10.3/' DENSLO=',  00796000
     $E10.3/' COEFF2=',E10.3/' VELOUT=',E10.3/' SHRINK=',E10.3////)     00797000
62    FORMAT('OWARNING:DTW=',E10.3,'##########')                        00798000
72    FORMAT(' X',9X,'T',9X,'TSAVE     FE',8X,'VAIR      G',9X,'D32',   00799000
     $7X,'VDROPS',4X,'RTIME',5X,'YAIR',6X,'SET',7X,'JEV  ITER')         00800000
82    FORMAT(//////' END OF JET ZONE  ',50('*')////)                    00801000
102   FORMAT('1START OF JET ZONE  ',50('*')////)                        00802000
112   FORMAT('1MAIN ZONE OF DRYER',50('*')////)                         00803000
122   FORMAT('0########NO CONVERG.:X,TEST,E,DAM,AM,TSAVE,T=',7E10.3)    00804000
132   FORMAT('0')                                                       00805000
142   FORMAT(13X,'TS(J) = ',14F7.1)                                     00806000
152   FORMAT(13X,'TDR(J)= ',14F7.1)                                     00807000
162   FORMAT(13X,'FSIZE = ',14F7.4)                                     00808000
172   FORMAT(13X,'V(J)  = ',14F7.2)                                     00809000
182   FORMAT(13X,'RTI(J)= ',14F7.2)                                     00810000
192    FORMAT(1X,11E10.3,2I5)                                           00811000
```

```
202   FORMAT(//////' END OF MAIN ZONE  ',50('*')///)                          00812000
212   FORMAT('1EVAPORATION VS DISTANCE'///)                                    00813000
222    FORMAT('1 EFFECTIVE AIR TEMPERATURE VS DISTANCE'///)                    00814000
232   FORMAT('1SAUTER MEAN DIAMETER VS DISTANCE'///)                           00815000
242   FORMAT(///' RADIATION PARAMETERS *****'/' FCL=',E10.3/' SH=',            00816000
     $E10.3/' CRAD=',E10.3//)                                                 00817000
      END                                                                     00818000
```

```
      SUBROUTINE PROFIL(ANOZ)                                                 00819000
C SUB TO CALC INITIAL TEMP,VEL(AIR),ENTRAINMENT PROFILES                      00820000
C TO CALC ENTRAINMENT USE EQN BY DAVIES-REF G13                               00821000
C FOR ALL OTHERS USE ABRAMOVITCH(REF.WKBK8 P.128)                             00822000
      COMMON/INIT/VINI(1001),YINIT(1001),G(1001),TINIT(1001),X(1001),         00823000
     $RJET,VO,GO,TO,YO,FO,VEXT,GEXT,TEXT,YEXT,NP1,NP2,NPT,NP3                 00824000
     $,TUIN(1001),TUSC(1001),TUINO,TUIN1,TUSCO,TUSC1,TLOSS,DENSF,HAJ          00825000
      IF(NP1.EQ.1)RETURN                                                      00826000
      HAJ=HAJ*.01745                                                          00827000
      HR=TAN(HAJ)/TAN(.2164)                                                  00828000
      IF(HR.EQ.0.)HR=1.                                                       00829000
      IF(ANOZ.GT.0.)GOTO 60                                                   00830000
C                                                                             00831000
C PROFILE FOR PRESSURE NOZZLE                                                 00832000
      RJ2=RJET*RJET                                                           00833000
      VDIF=(VO-VEXT)/HR                                                       00834000
      VEQ=0.45*VDIF                                                           00835000
      DTEQ=(TO-TEXT)/HR*.75                                                   00836000
      DYEQ=(YO-YEXT)/HR*.75                                                   00837000
      RHOG=1.293*273./TEXT                                                    00838000
      AJ=DENSF/RHOG                                                           00839000
      AJ1=SQRT(AJ)                                                            00840000
      XO=RJET*(10.7*(1.73*AJ1-1.)-13.6*AJ1)                                   00841000
      BB=3.14159*2.*RJ2*RHOG*VEXT                                             00842000
      GCOEF=1.82*VDIF*RJ2*AJ*RHOG                                             00843000
      DO 70 I=1,NP3                                                           00844000
      G(I)=0.                                                                 00845000
      VINI(I)=VO                                                              00846000
      TINIT(I)=TO                                                             00847000
      YINIT(I)=YO                                                             00848000
      IF(X(I).LE.XO)GOTO 70                                                   00849000
      R$=RADJET(X(I),RJET,RHOG,DENSF)                                         00850000
      RR$=R$*R$                                                               00851000
      AA=SQRT(1.+1.5*RR$/AJ)-1.                                               00852000
      G(I)=GCOEF*AA+BB*RR$                                                    00853000
      G(I)=G(I)*HR                                                            00854000
      IF(G(I).GT.GEXT)G(I)=GEXT                                               00855000
      RATIO=2.25*AJ/RR$*AA                                                    00856000
      RATIO1=RATIO*0.73                                                       00857000
      VINI(I)=VEQ*RATIO+VEXT                                                  00858000
      TINIT(I)=DTEQ*RATIO1+TEXT                                               00859000
      YINIT(I)=DYEQ*RATIO1+YEXT                                               00860000
70    CONTINUE                                                                00861000
      GOTO 80                                                                 00862000
60    CONTINUE                                                                00863000
C                                                                             00864000
C PROFILE FOR PNEUMATIC NOZZLE                                                00865000
      AJ=1.+FO/GO                                                             00866000
      AS=FO/(GO+FO)                                                           00867000
      VEQ=.563*(VO-VEXT)/HR                                                   00868000
      DTEQ=(TO-TEXT)/HR*.75                                                   00869000
      DYEQ=(YO-YEXT)/HR*.75                                                   00870000
      G(1)=GO                                                                 00871000
      TINIT(1)=TO                                                             00872000
      VINI(1)=VEQ                                                             00873000
      YINIT(1)=YO                                                             00874000
      DO 10 I=2,NP3                                                           00875000
      G(I)=GO*(.115*X(I)/RJET-1.)                                             00876000
      G(I)=G(I)*HR                                                            00877000
      IF(G(I).LE.GO)G(I)=GO                                                   00878000
      IF(G(I).GT.GO+GEXT) G(I)=GO+GEXT                                        00879000
      VINI(I)=VEQ*12.4/(X(I)/RJET+12.4)+VEXT                                  00880000
      RATIO=0.73*(VINI(I)-VEXT)/VEQ                                           00881000
      DT=DTEQ*RATIO                                                           00882000
      TINIT(I)=TEXT+DT                                                        00883000
      DY=DYEQ*RATIO                                                           00884000
      YINIT(I)=YEXT+DY                                                        00885000
   10 CONTINUE                                                                00886000
80    CONTINUE                                                                00887000
      IF(NP1.EQ.NP3)GOTO 50                                                   00888000
C SET UP PROFILES FOR TRANSITION ZONE                                         00889000
      NDEL=NP1-NP3                                                            00890000
      GGRAD=(G(NP1+1)-G(NP3))/NDEL                                            00891000
      VGRAD=(VINI(NP1+1)-VINI(NP3))/NDEL                                      00892000
      TGRAD=(TINIT(NP1+1)-TINIT(NP3))/NDEL                                    00893000
      YGRAD=(YINIT(NP1+1)-YINIT(NP3))/NDEL                                    00894000
      DO 30 I=NP3+1,NP1                                                       00895000
      G(I)=G(I-1)+GGRAD                                                       00896000
      VINI(I)=VINI(I-1)+VGRAD                                                 00897000
      TINIT(I)=TINIT(I-1)+TGRAD                                               00898000
      YINIT(I)=YINIT(I-1)+YGRAD                                               00899000
30    CONTINUE                                                                00900000
50    CONTINUE                                                                00901000
```

```
      PRINT 12                                                          00902000
12    FORMAT('0INITIAL PROFILES OF AIR STREAMS'/' X',9X,'TUIN',6X,      00903000
     $ 'TUSC      TINIT     YINIT     VINI      G'/)                    00904000
      DO 100 I=1,NPT,5                                                  00905000
100   PRINT 2,X(I),TUIN(I),TUSC(I),TINIT(I),YINIT(I),VINI(I),G(I)       00906000
2     FORMAT(1X,9E10.3)                                                 00907000
      END                                                               00908000
```

```
      SUBROUTINE PROFIl                                                 00909000
      COMMON/ INIT/VINI(1001),YINIT(1001),G(1001),TINIT(1001),X(1001),  00910000
     $RJET,VO,GO,TO,YO,FO,VEXT,GEXT,TEXT,YEXT,NP1,NP2,NPT,NP3           00911000
     $,TUIN(1001),TUSC(1001),TUINO,TUIN1,TUSCO,TUSC1,TLOSS,DENSF,HAJ    00912000
      IF(NP2.EQ.0)RETURN                                                00913000
      GAM=GO+GEXT                                                       00914000
      YAM=(YO*GO+YEXT*GEXT)/GAM                                         00915000
      TAM=(TO*GO+TEXT*GEXT)/GAM                                         00916000
      VAM=VEXT*GAM/GEXT                                                 00917000
      TU=TUINO*TUIN1*TUSCO*TUSC1                                        00918000
      IF(TU.EQ.0.)GOTO 20                                               00919000
      BI=1./TUINO                                                       00920000
      AI=(1./TUIN1-BI)/X(NPT)                                           00921000
      AS=(TUSC1-TUSCO)/X(NPT)                                           00922000
      BS=TUSCO                                                          00923000
20    CONTINUE                                                          00924000
      DO 10 I=1,NPT                                                     00925000
      G(I)=GAM                                                          00926000
      YINIT(I)=YAM                                                      00927000
      TINIT(I)=TAM-TLOSS*X(I)                                           00928000
      VINI(I)=VAM*TINIT(I)/TEXT                                         00929000
      IF(TU.EQ.0.)GOTO 10                                               00930000
      TUIN(I)=1./(AI*X(I)+BI)                                           00931000
      TUSC(I)=AS*X(I)+BS                                                00932000
10    CONTINUE                                                          00933000
      RETURN                                                            00934000
      END                                                               00935000
```

```
      FUNCTION F1(W,E)                                                  00936000
C DERIVATIVE OF DROPLET VELOCITY SQUARED WRT DISTANCE                   00937000
      COMMON /VELEP/ DENSLO,WSOL,WLIQ,VLIQ,COEFF2,HTLAT,DENLIQ,ECRIT,  00938000
     $DCRIT,TAIR,VAIR,DENS,VISKIN,THCOND,TWB,DENSL,DO,D,RE,V,CORESQ,    00939000
     $WAGRAD,SQVRT,CRAD,RADIOS,QRCP1,CSS                                00940000
      F1=WAGRAD                                                         00941000
      IF(E.GT.1.)E=1.                                                   00942000
      IF(VLIQ*E.GE.1.)RETURN                                            00943000
C CALC. DIAMETER AND DENSITY                                            00944000
      IF(E.LT.ECRIT)GOTO 20                                             00945000
      D=DCRIT                                                           00946000
      DENSL=DENSLO*(1.-WLIQ*E)/(1.-VLIQ*ECRIT)                          00947000
      GOTO 30                                                           00948000
20    D=DO*(1.-VLIQ*E)**(1./3.)                                         00949000
      DENSL=DENSLO*(1.-WLIQ*E)/(1.-VLIQ*E)                              00950000
30    CONTINUE                                                          00951000
      IF(D.LE.0.)RETURN                                                 00952000
C CALC. F1                                                              00953000
      IF(W.LE.0)W=1.E-8                                                 00954000
      V=SQRT(W)                                                         00955000
      VREL=V-VAIR                                                       00956000
      VRELAB=SQRT(VREL*VREL+SQVRT)                                      00957000
      RE=D*VRELAB/VISKIN                                                00958000
      CD=DRAG(RE)                                                       00959000
      IF(CORESQ.GT.0.1)F1=-1.5*CD*DENS/D/DENSL*VREL*VRELAB+2*9.8        00960000
      RETURN                                                            00961000
      END                                                               00962000
```

```
      FUNCTION F2(W,E)                                                  00963000
C DERIVATIVE OF FRACTIONAL EVAPORATION WRT DISTANCE                     00964000
      COMMON /VELEP/ DENSLO,WSOL,WLIQ,VLIQ,COEFF2,HTLAT,DENLIQ,ECRIT,  00965000
     $DCRIT,TAIR,VAIR,DENS,VISKIN,THCOND,TWB,DENSL,DO,D,RE,V,CORESQ,    00966000
     $WAGRAD,SQVRT,CRAD,RADIOS,QRCP1,CSS                                00967000
C RE,D,V&DENSL HAVE BEEN CALCD BY F1 WHICH IS ALWAYS CALLED BEFORE F2   00968000
      F2=0.                                                             00969000
      IF(E.GE.1.)RETURN                                                 00970000
      B=CSS*(TAIR-TWB)/HTLAT                                            00971000
      A=1./(1.+B)                                                       00972000
      QC=(2.+.53*SQRT(RE))*THCOND*(TAIR-TWB)/D*A                        00973000
      QR=CRAD*(RADIOS-TWB**4.)                                          00974000
      QRCP1=1.                                                          00975000
      IF(QC.NE.0.)QRCP1=1.+QR/QC                                        00976000
      IF(QC+QR.LE.0.)RETURN                                             00977000
      F2=COEFF2*(QC+QR)*D*D/V/DO/DO/DO                                  00978000
      RETURN                                                            00979000
      END                                                               00980000
```

```
      FUNCTION DRAG(RE)                                                 00981000
C APPROXIMATN TO STD DRAG CURVE,COMBINING EQNS BY SCHILLER&NAUMANN,     00982000
C BEARD&PRUPPACHER,CLIFF&GAUVIN-CORRECT TO 3PC.                         00983000
      IF(RE.EQ.0)RETURN                                                 00984000
      C=24./RE                                                          00985000
      DRAG=C                                                            00986000
      IF(RE.GT.0.4.AND.RE.LE.2.)DRAG=C*(1.+.1*RE)                       00987000
      IF(RE.GT.2.)DRAG=C*(1.+.15*RE*.687)+.42/(1.+4.25E4/RE**1.16)      00988000
      RETURN                                                            00989000
      END                                                               00990000
```

```
      SUBROUTINE PLOT1(Y,N,XO,DX,YMIN,YMAX,NSPACE)                      00991000
C PLOT A POINT EVERY NSPACE VALUES                                      00992000
C DX*NSPACE=X-INCREMENTS BW PLOTTED POINTS                              00993000
C Y=ARRAY TO BE PLOTTED                                                 00994000
C XO=INITIAL X-VALUE                                                    00995000
C IF YMIN & YMAX ARE UNKNOWN, SUPPLY THEM AS EQUAL NOS.                 00996000
C N=NO. OF POINTS PLOTTED                                               00997000
      DIMENSION Y(N)                                                    00998000
      IF(YMAX.GE.YMIN)GOTO 35                                           00999000
      AA=YMIN                                                           01000000
      YMIN=YMAX                                                         01001000
      YMAX=AA                                                           01002000
35    CONTINUE                                                          01003000
      IF((YMAX-YMIN).NE.0.)GO TO 70                                     01004000
      YMAX=-1.E30                                                       01005000
      YMIN=+1.E30                                                       01006000
      DO 10 I=1,N                                                       01007000
      IF(Y(I).GT.YMAX)YMAX=Y(I)                                         01008000
   10 IF(Y(I).LT.YMIN)YMIN=Y(I)                                         01009000
   70 CONTINUE                                                          01010000
      REAL LINE(101),MINUS                                              01011000
      DATA BLANK,PLUS,MINUS,BAR,PLT/1H ,1H+,1H-,1H:,1H*/                01012000
      X=XO                                                              01013000
      DO 2 I=1,101                                                      01014000
      LINE(I)=MINUS                                                     01015000
    2 IF(MOD(I-1,10).EQ.0) LINE(I)=PLUS                                 01016000
      WRITE(6,3) YMIN,YMAX                                              01017000
    3 FORMAT(15X,E15.5,80X,E15.5)                                       01018000
      DY=(YMAX-YMIN)/100.                                               01019000
      ITER=1                                                            01020000
  100 YY=Y(ITER)                                                        01021000
      IY=IFIX((YY-YMIN)/DY+0.5) + 1                                     01022000
      IF(IY.LT.1.OR.IY.GT.101) GO TO 4                                  01023000
      LINE(IY)=PLT                                                      01024000
    4 WRITE(6,5)LINE                                                    01025000
    5 FORMAT('+'/20X,101A1)                                             01026000
      IF(MOD(LINES,10).EQ.0)WRITE(6,8)X                                 01027000
    8 FORMAT('+',3X,E15.5)                                              01028000
      LINES=LINES+1                                                     01029000
      IF(MOD(LINES,10).EQ.0) GO TO 9                                    01030000
      DO 6 I=1,101                                                      01031000
      LINE(I)=BLANK                                                     01032000
    6 IF(MOD(I-1,10).EQ.0) LINE(I)=BAR                                  01033000
7     X=X+DX*NSPACE                                                     01034000
      ITER=ITER+NSPACE                                                  01035000
      IF(ITER.GT.N) RETURN                                              01036000
      GO TO 100                                                         01037000
    9 DO 310 I=1,101                                                    01038000
      LINE(I)=MINUS                                                     01039000
  310 IF(MOD(I-1,10).EQ.0) LINE(I)=PLUS                                 01040000
      GO TO 7                                                           01041000
      END                                                               01042000
```

```
      SUBROUTINE SPRAY(D,DN,NSIZE)                                      01043000
      DIMENSION D(20),DN(20)                                            01044000
C SUB TO READ SPRAY SIZE DISTN INTO MAIN PROG                           01045000
C     N-T DISTRIBUTION,DELTA=0.5                                        01046000
      READ(5,1)NSIZE,DVS                                                01047000
1     FORMAT(I2,8X,F10.0)                                               01048000
      DDIA=DVS**2.5/NSIZE/0.94                                          01049000
C FACTOR 0.94 IS USED TO CORRECT FOR DIFFERENCE BW ANALYTICAL VALUE      01050000
C AND NUMERICALLY CALCD VALUE OF DVS                                    01051000
      DO 20 I=1,NSIZE                                                   01052000
20    D(I)=I*DDIA                                                       01053000
      B=SQRT(GAMMA(12.)/GAMMA(10.)/(DVS/0.94))                          01054000
      DO 10 I=1,NSIZE                                                   01055000
      X=D(I)                                                            01056000
      DN(I)=1.E15*X*X*EXP(-B*SQRT(X))                                   01057000
10    CONTINUE                                                          01058000
      PRINT 2                                                           01059000
2     FORMAT('OSUBR. SPRAY RESULTS'/'ODIA       NUMBER'/)               01060000
      PRINT 22,((D(I),DN(I)),I=1,NSIZE)                                 01061000
   22 FORMAT(1X,2E10.3)                                                 01062000
      PRINT 32,DVS                                                      01063000
32    FORMAT(' D32=',E10.3//)                                           01064000
      RETURN                                                            01065000
      END                                                               01066000
```

```
      FUNCTION FCURVE(AMOIST,D,RATE,AMOISO)                             01067000
C RELATIVE DRYING RATE(AS COMPARED WITH DROPLET OF LIQUID)              01068000
C AMOIST=MOISTURE CONTENT WET BASIS                                     01069000
C D=DROPLET DIAMETER                                                    01070000
C RATE=MEAN EVAPORATION RATE(DE/DT) UP TO THIS POINT                    01071000
      FCURVE=1.                                                         01072000
      AMOCR=AMOISO                                                      01073000
      XCR=AMOCR/(1.-AMOCR)                                              01074000
      IF(AMOIST.GE.AMOCR)RETURN                                         01075000
      X=AMOIST/(1.-AMOIST)                                              01076000
      FCURVE=X/XCR                                                      01077000
      RETURN                                                            01078000
      END                                                               01079000
```

```
      SUBROUTINE WBULB(TA,YA,TS,YS,DER,CS,RS,TSO,INDEX)                 01080000
C IF(INDEX.GT.0)SUBROUTINE CALC.ADIABATIC SATURATION TEMP.&HUMIDITY     01081000
C TS,YS FROM AIR CONDITIONS TA,YA                                       01082000
C IF(INDEX.LT.0) SUBROUTINE CALC SATURATION HUMIDITY YS FROM TS         01083000
C SUBR. ALSO RETURNS DER(DERIV.OF SATURATN CURVE)&CS(SATED AIR SP.HT)   01084000
C SATURATION CURVE GIVEN BY CURVE-FITTED RIEDEL-MILLER-PLANK EQN        01085000
C LOG(P)=A/TS+B+C*TS+D**2 ,TS=300-380K,P IN ATM                         01086000
C CW=WATER VAPOUR SPEC. HT                                              01087000
C CA=AIR SPEC. HT                                                       01088000
C HT=LATENT HT OF EVAPORATION                                           01089000
C RS=RELATIVE HUMIDITY OF AIR IN EQM WITH AQUOUS SOLUTION               01090000
C TSO=1ST ESTIMATE OF ADIABATIC SATURATION TEMP. OF SOLUTION            01091000
C                                                                       01092000
C                                                                       01093000
      COMMON/WETBUL/A,B,C,D,D2,CA,CW,HT,ICNT                            01094000
      ICNT=ICNT+1                                                       01095000
      IF(ICNT.GT.1)GOTO 30                                              01096000
      A=-.63488E4                                                       01097000
      B=22.536                                                          01098000
      C=-.019639                                                        01099000
      D=.13010E-4                                                       01100000
      D2=D*2.                                                           01101000
      CA=1.015E3                                                        01102000
      CW=1.89E3                                                         01103000
      HT=2.46E6                                                         01104000
30    CONTINUE                                                          01105000
      IF(TSO.LT.273.)TSO=350.                                           01106000
      IF(INDEX.GT.0)TS=TSO                                              01107000
      DO 10 I=1,20                                                      01108000
C CALC. SATURATION HUMIDITY                                             01109000
```

```
C                                                                       01110000
      P=A/TS+B+(C+D*TS)*TS                                              01111000
      P=EXP(P)                                                          01112000
      P=P*RS                                                            01113000
      IF(P.LT.1.)GOTO 40                                                01114000
      DO 50 ITER=1,30                                                   01115000
      TS=TS-5.                                                          01116000
      P=A/TS+B+(C+D*TS)*TS                                              01117000
      P=EXP(P)                                                          01118000
      P=P*RS                                                            01119000
      IF(P.LT.1.)GOTO 40                                                01120000
50    CONTINUE                                                          01121000
40    CONTINUE                                                          01122000
      YS=.622*P/(1.-P)                                                  01123000
C CALC. DERIVATIVE OF YS VS TS USING CHAIN RULE                         01124000
C                                                                       01125000
      DER=-A/TS/TS+C+D2*TS                                              01126000
      DER=DER*P                                                         01127000
      DER=0.622  /(1.-P)/(1.-P)*DER                                     01128000
C CALC THE ADIABATIC-SATURATION SLOPE                                   01129000
      CS=YS*CW+(1.-YS)*CA                                               01130000
      IF(INDEX.LT.0)RETURN                                              01131000
      SL=HT/CS                                                          01132000
C CALC. NEW APPROXIMATION                                               01133000
C                                                                       01134000
      DTS=-(SL*(YS-YA)+(TS-TA))/(SL*DER+1.)                             01135000
      TS=TS +DTS                                                        01136000
      IF(TS.GT.500.)TS=500.                                             01137000
      IF(ABS(DTS).LE.0.02)RETURN                                        01138000
10    CONTINUE                                                          01139000
      PRINT 2,TSO,TS                                                    01140000
2     FORMAT(' WARNING***SUB.WBULB DOESNT CONVERGE. TSO,TS=',2E10.3)    01141000
      RETURN                                                            01142000
      END                                                               01143000
```

```
      FUNCTION RADJET(X,RO,RHOG,RHOL)                                   01144000
C     DIMLESS RAD. OF GAS JET INDUCED BY PRESSURE NOZZLE,R/RO           01145000
C     X=DIST. FROM ORIFICE                                              01146000
C     RHOG,RHOL=DENSITIES                                               01147000
C     AJ=RHOL/RHOG                                                      01148000
C     XO=POSITION OF POLE                                               01149000
C     SUBSCRIPT$=DIMLESS                                                01150000
C     ST.SEGMENT APPROX. TO ABRAMOVITCH EQN. 12.318-ALSO WKBK 8P.174    01151000
      X$=X/RO                                                           01152000
      COMMON/RADJ/R$(501),XI$(501),XO$,ICALL                            01153000
      ICALL=ICALL+1                                                     01154000
      IF(ICALL.GT.1) GO TO 20                                           01155000
      AJ=RHOL/RHOG                                                      01156000
      AJ1=SQRT(AJ)                                                      01157000
      XO$=10.7*(1.73*AJ1-1.)-13.6*AJ1                                   01158000
      DLNR=(ALOG(1000.)-ALOG(3.))/500                                   01159000
      DO 10 I=1,501                                                     01160000
      R$(I)=3.*EXP((I-1)*DLNR)                                          01161000
      AA=R$(I)/AJ1                                                      01162000
      AB=AA*AA                                                          01163000
      AC=SQRT(1.+1.48*AB)                                               01164000
      AD=R$(I)+AJ1*(ALOG(1.22*AA+AC)-0.25*ATAN                          01165000
     $(1.28*AA*(AC-0.24)/(AC+0.31*AB)))                                 01166000
      XI$(I)=AD/0.22+XO$                                                01167000
   10 CONTINUE                                                          01168000
   20 CONTINUE                                                          01169000
      IF(X$.GT.XO$) GO TO 80                                            01170000
      RADJET=0.                                                         01171000
      RETURN                                                            01172000
   80 CONTINUE                                                          01173000
      IF(X$.GE.XI$(1)) GO TO 30                                         01174000
      RADJET=3*(X$-XO$)/(XI$(1)-XO$)                                    01175000
      RETURN                                                            01176000
   30 CONTINUE                                                          01177000
      IF(X$.LE.XI$(501)) GO TO 40                                       01178000
      RADJET=0.22*(X$-XO$)                                              01179000
      RETURN                                                            01180000
   40 CONTINUE                                                          01181000
      DO 50 I=1,501                                                     01182000
      IF(X$.GT.XI$(I)) GO TO 60                                         01183000
   50 CONTINUE                                                          01184000
   60 CONTINUE                                                          01185000
      I=I+1                                                             01186000
      D1=XI$(I)-X$                                                      01187000
      D2=X$-XI$(I-1)                                                    01188000
      RADJET=(R$(I)*D2+R$(I-1)*D1)/(D1+D2)                              01189000
      RETURN                                                            01190000
      END                                                               01191000
```